TESTS OF REINFORCED CONCRETE COLUMNS: RELATION OF LENGTH RATIO TO STRENGTH

BY

VICTOR BYRON FREDENHAGEN

AND

HAROLD EUGENE TOBEY

Metz Reference Room
Civil Engineering Department
B106 C. E. Building
University of Illinois
Urbana, Illinois 61801

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This is to certify that the thesis prepared in the Department of Theoretical and Applied Mechanics by VICTOR BYRON FREDENHAGEN and HAROLD EUGENE TOBEY entitled Tests of Reinforced Concrete Columns: Relation of Length Ratio to Strength is approved by me as fulfilling this part of the requirements for the degree of Bachelor of Science in Civil Engineering.

D. A. Abrams
A N Talbot
Instructors in Charge.

Approved:

A N Talbot
Professor of Municipal and Sanitary Engineering
In Charge of Theoretical and Applied Mechanics.

Approved:

Ira O. Baker.
Professor of Civil Engineering.

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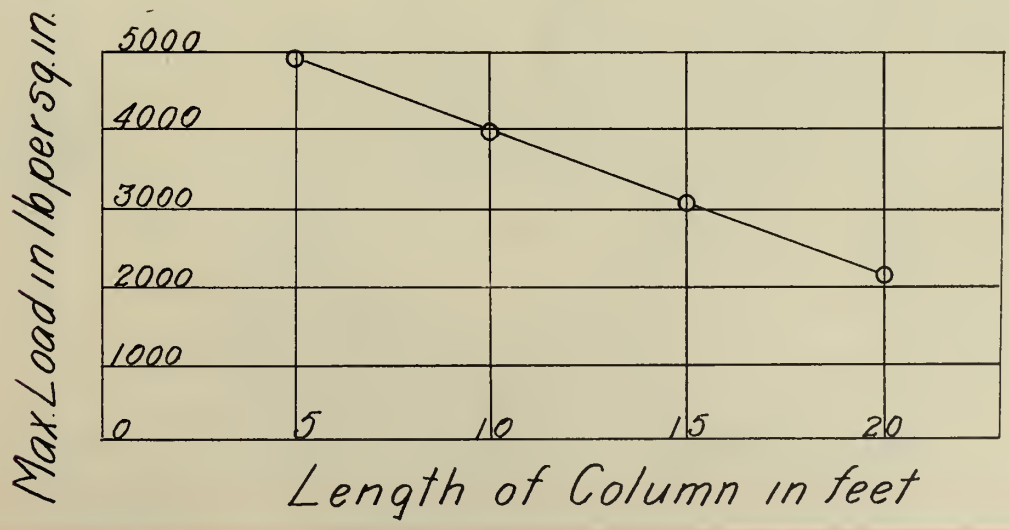
TESTS OF PLAIN AND REINFORCED CONCRETE COLUMNS.

INTRODUCTION.

The relation of the length ratio to the strength of plain and reinforced columns is a subject which has, in the past, been entirely misconceived. Until last year (1909) when the University of Illinois made a series of tests on spirally reinforced concrete columns of various lengths, it was generally stated that for lengths up to 20 or 25 diameters, the length did not have any effect upon the strength of concrete columns. Last year's tests showed that the length exerts a very material influence upon the strength of spirally-reinforced concrete columns of lengths between 5-and 20-ft. for columns 12 in. in diameter.

A glance at the curve (taken from the Thesis of James and Shaw, 1909) shows the general characteristics of, and the effect of length upon, the strength of spirally reinforced columns. These columns were 12 in. in diameter.

Curve showing the Relation of Length of Column to its Strength.



The curve was plotted using the maximum unit stresses as ordinates and the lengths as abscissae. Each point plotted is the average ultimate of the strengths of three columns of the given length. These columns contained 1.65 % spiral reinforcement, and had no longitudinal reinforcement. If the line be prolonged for columns of longer than 20 ft. it will be found that a column 34 ft. in length would have no strength. However the curve cannot be taken as applicable for any length of column except within the limits of the lengths tested.

The series of tests taken up in this thesis is an outgrowth and an extension of the former tests. The lengths of columns tested this year (1909) and the proportion of material used were the same as those of last year's tests. The tests this year were made upon plain columns, columns reinforced with longitudinal rods only, and columns reinforced by both spirals and longitudinal rods. A study of the data of these tests gives some new information on the relation of the length ratio of plain and reinforced concrete columns to their strength.

Scope of the Thesis: Tests of concrete and reinforced concrete columns in the various laboratories have provided much valuable information as to the action of short concrete columns (the usual length seems to be about 8 to 10 ft.) under axial loading. These series of tests on both plain and reinforced concrete columns of varying lengths have been carried on under parallel conditions of cement, manufacture, and storage, so

determine what effect the length has upon the load that the column can be relied upon to carry before failure. Three series of tests were made upon columns varying in length from about 5 to 20 ft. One series of tests was made on plain concrete columns, and one upon columns which were reinforced by longitudinal rods only, and another upon columns which were reinforced with both longitudinal rods and spiral-hooping.

This thesis is a report on the testing to destruction of the 36 columns listed in Table 4 together with a description of the phenomena of the tests and a discussion of the results, especially in regard to the effect of the length upon the strength of plain and reinforced concrete columns and as to the action of columns of various lengths under axial loading. The tests also give some information upon the proportion of the load which vertical reinforcement takes when used alone in concrete columns and also upon the proportion taken by the spiral hooping.

MATERIALS.

General: The materials used in the construction of the columns were crushed limestone, sand, portland cement, steel rods, and spiralled column units. These materials were similar to those used in first class reinforced concrete construction. The cement and steel were furnished for these tests by the manufacturers. The stone and sand were purchased in the open market.

STONE: The stone was crushed limestone from Kankakee, Illinois, and was screened to pass a 1 1/4- in. screen and be retained on a 1/4-in. screen. It was all taken from one shipment, and was fairly uniform in quality. It contained about 40% voids and weighed about 82 lb. per cubic foot. Below is a sieve analysis of the stone, the values given being the average of two trials.

Table 1.

Mechanical Analysis of Stone.

Sieve	Per Cent Passing.
1 1/4 in.	100.0
3/4 in.	98.6
1/2 in.	83.3
3/8 in.	63.8
No. 3	43.0
No. 5	12.2
No. 16	7.4
No. 18	7.0
No. 30	6.6
No. 50	5.1
No. 200	4.5

SAND : The sand came from Attica, Indiana. It was ordinary bank run sand screened to pass a 1/4- in. mesh. It was of good quality, well graded, and fairly clean. It contained about 1 to 2 % clay and 26 % voids. Table 2 gives the mechanical analysis of the sand.

Table 2.

Mechanical Analysis of Sand.

Sieve No.	Per Cent Passing.
5	97.8
16	55.4
18	43.2
30	27.3
150	2.1
200	1.5

CEMENT: Universal portland cement was used throughout in making the columns. The tensile tests of the cement are given in the following table. The tests were made according to standard methods.

Table 3.

Tensile Tests of Universal Portland Cement.

Sample No.	7 day tests Neat Cement	1:3	28 tests Neat Cement	1:3
1	670	190	697	297
2	629	219	678	328
3	613	217	649	315

Each value given is the average of 5 briquet tests.

STEEL: The reinforcing steel consisted of longitudinal rods and spiralled column units. The longitudinal rods were all 3/4- in. plain round rods of mild steel. The spiralled column units were made by the American System of Reinforcing Concrete, of Chicago. The spirals were usually one continous rod from top to bottom but in case they were spliced the rods were doubled on half the circumference and bent inward about 4 in. All spiralled rods were 1/4-in. in diameter formed into a 12-in. spiral having a pitch of 1-in. The spiral rods were held to the right pitch by three vertical bands. See photograph Page 65. All spirals were made of high carbon steel.

Table 4.

List of Plain and Reinforced Concrete Columns Tested.

(Series of 1910)

All columns 12 in. in diameter; 1-2-4 concrete by loose volume, 1 cu. ft. cement = 95 lb.

Column No.			Length	Reinforcement
8501	8502	8503	5 ft.	None
8601	8602	8603	10	
8701	8702	8703	15	
8801	8802	8803	20	
8511"	8512	8513	5#	Six 1-in. rounds inside 10-in. circle
8611	8612	8613	10	Six 3/4in. rounds inside 10-in. circle
8711	8712	8713	15	
8811	8812	8813	20	
8521	8522	8523	5	(1/4-in. spiral, 12 in. dia., pitch
8621	8622	8623	10	(1 in. 3/4-in. rounds.
8721	8722	8723'	15	
8821	8822	8823	20	

' Vertical steel inside a 10-in. circle; in all other columns vertical steel in contact with inside of spiral.

Tested by Mr. D. Q. McComb 1910.

" Rods ~~inside~~ out a 10-in. circle.

TEST PIECES.

COLUMNS AND AUXILIARY TEST SPECIMENS

An effort was made to have the materials of Construction and the conditions of fabrication for the test specimens as nearly uniform as possible. Three columns of each length and kind of reinforcement were made. The concrete for each column was made in one batch except for the 5-ft. columns, when one batch was used for two columns. Three classes of columns were made (a) 5-,10-,15-, and 20-ft. plain concrete columns, (b) 5-,10-, 15-and 20-ft. columns reinforced with longitudinal rods only, and (c) 5-,10-,15-and 20-ft. reinforced columns having both longitudinal rods and spiral hooping. Realizing that the strength of concrete is largely dependent upon the materials used in its fabrication and upon the method of storage, a special effort was made to have these factors as nearly uniform as possible. All of the columns had a circular cross-section and were about 12in. in diameter; and all were of a 1-2-4- mixture by loose volume, 95 lb. of cement being considered as one cubic foot. All the columns were stored in the same manner, and were tested when about 60 days old. The columns in any one set were made at different times and thus the variations in material and manufacture were distributed throughout the set of specimens.

PLAIN CONCRETE COLUMNS : Twelve columns with no reinforcement were tested. There were three columns of each of the following lengths 5,10,15 and 20 ft. In general these columns were not very straight, there were breaks in the alignment where the

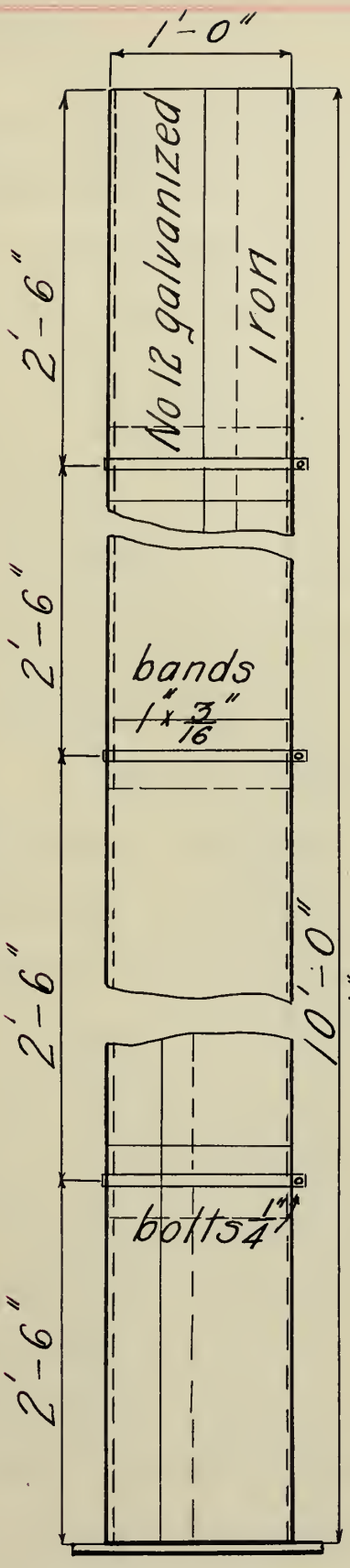
sections of the forms joined each other, and in addition some them were out of plumb. Further data on these irregularities will be given in the notes on the individual column tests.

LONGITUDINALLY REINFORCED COLUMNS: Twelve columns reinforced with longitudinal rods only were tested. They consisted of four sets of three columns of each length 5,10,15 and 20 ft. respectively. The three 5-ft. columns were tested by Mr. D. Q. McComb. ~~The~~ The reinforcement for all except the 5ft. columns consisted of six 3/4-in. plain round rods of mild steel placed inside a 10-in. circle, as noted in Table 4 the 5-ft. columns of this series were reinforced with six 1-in. plain round rods. The spacing bands which held the rods in place were about 1-in. by 1/10-in., with electrically welded joints. The rods were held in place by soft iron wires which passed around the rods and through holes drilled in the band. In the 15- and 20-ft. columns three or four spacing bands were used and in the 5- and 10-ft. columns two or three bands were used. The function of these bands was to hold the rods in position while the concrete was being placed in the forms. Later investigation showed that they served this purpose very well. All of the rods were squared and cut to equal lengths. The rods rested directly upon the lower bearing plate and they were intended to touch the upper bearing plate in the same manner, but in several instances they did not do so. This was due to the shrinkage of the concrete in setting and to the fact that it was necessary to set the upper plate in plaster of paris to get a uniform bearing over

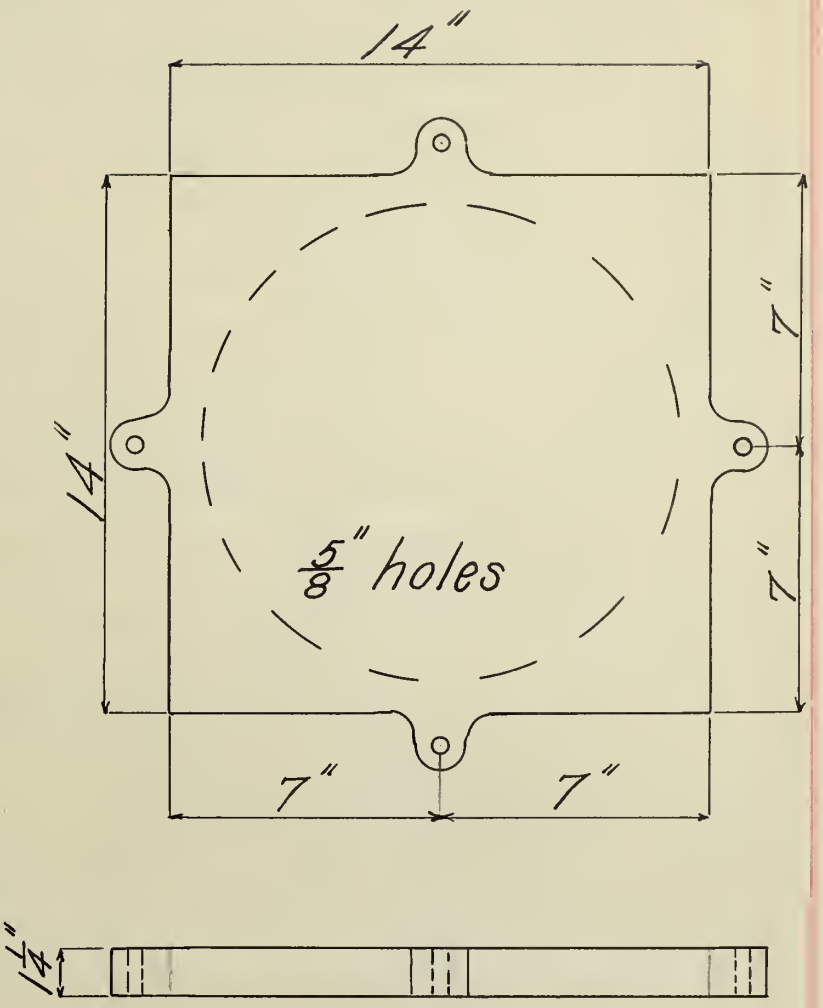
the top surface. Usually the rods were within 3/16-in. of the upper bearing plate but in one instance, Column 8711 they were about 3/8-in. away from it.

These columns were straighter than the plain columns. The joints, where one section of the form lapped over another, did not show as they did in the plain columns; but these columns possessed the fault of being out of plumb.

SPIRAL-HOOPED REINFORCED COLUMNS: Twelve columns, reinforced with spiral hooping and longitudinal rods were tested. These were of four different lengths 5, 10, 15, and 20ft.; three of each length being made as in the other two series. The spirals were 1/4-in. round wire of high carbon steel, having a pitch of 1-in. and a diameter of the spiral of 12 in. In addition to the spiral reinforcement there were six 3/4-in. round rods of mild steel placed longitudinally inside the spirals. In all of the columns except Column 8723 the longitudinal rods were in contact with the inside of the spiral and spaced evenly around the circumference. In column 8723 the rods were placed in a 10-in. circle as in the case of the columns having only longitudinal rods. It will be observed that the column stood 536 lb. per sq. in. more stress than either of the other columns in the same set. All of the columns which were reinforced with spirals and longitidunal rods were straight. The sides were smooth and a good bond between the spirals and the concrete was secured. However, these columns were also out of plumb as they stood in the testing machine.



Forms for Columns
(A)



Details of Base Plate
(B)

Fig. 1

FORMS: The forms consisted of thin sheet iron as shown in Figure 1A and were held to the required diameter by iron bands fastened together with bolts. With the plain columns the forms were set up in sections, iron spacing bands being placed inside the joints to keep the form circular and to the proper diameter. These inside spacing bands were used also on the longitudnally reinforced columns, but in the spiralled columns they were not needed because the forms rested directly against the spirals. In all columns the forms rested on a cast iron base plate and were lined up vertically by means of an ordinary carpenter's level.

METHOD OF MAKING THE COLUMNS.

MIXING THE CONCRETE: The concrete was mixed by hand by men accustomed to making concrete test pieces and it was thought to be about uniform in composition throughout the entire series of test columns. The sand and cement were first mixed dry and turned until a uniform color was produced. The stone, which had been previously moistened, was then mixed with the dry sand and cement. The result was that each stone was throughly coated with mortar before the water was added. Finally the whole mass was turned until it was of uniform consistency. The concrete was mixed quite wet so that it would tamp readily into the forms and around the reinforcement. Water constantly flushed to the surface in filling the forms. The materials were all proportioned by loose volumes, 95 lb. of cement being considered one cu. ft. The weights of the other materials were taken as a

check on the quantity in each batch. This method of proportioning gives a richer mixture than the ordinary method of proportioning by loose volumes. The difference amounts to about 15% increase in the quantity of cement.

FILLING THE FORMS; The columns rested upon a cast iron base plate as shown in Figure 1B. The base plate was supposed to have been level, but in the process of filling the forms it was usually jarred out of position and as a result, the axis of the column was not perpendicular to the base and the column stood out of plumb in the testing machine. The concrete was deposited in the forms in layers of about 6 to 8-in. in thickness and tamped or churned; water being always present upon the surface. It was very difficult to keep the forms for the plain columns in true alignment, and quite often breaks showed up at the joints of the forms. Hoops were placed at every joint in the plain columns and in the columns reinforced with longitudinal rods only in order to keep the forms to the proper diameter. In the case of the spiralled columns, the forms rested against the spirals and there was no difficulity in keeping a straight alignment, but many of these were out of plumb.

STORAGE: All the columns were stored in the room in which they were made. The forms were left on for 7 days. The columns were wet frequently from a hose during the season of storage. The idea was to approach as nearly as possible the

actual conditions under which concrete dries or hardens in building construction. The air is the storage room ranged in temperature from 55° to 70° F. Some unavoidable changes in temperature occurred; but though these changes were considerable they could not have had any appreciable effect upon the strength. Photograph, Page 16, shows some of the longer columns during the season of storage. The forms are in place on two of the columns.

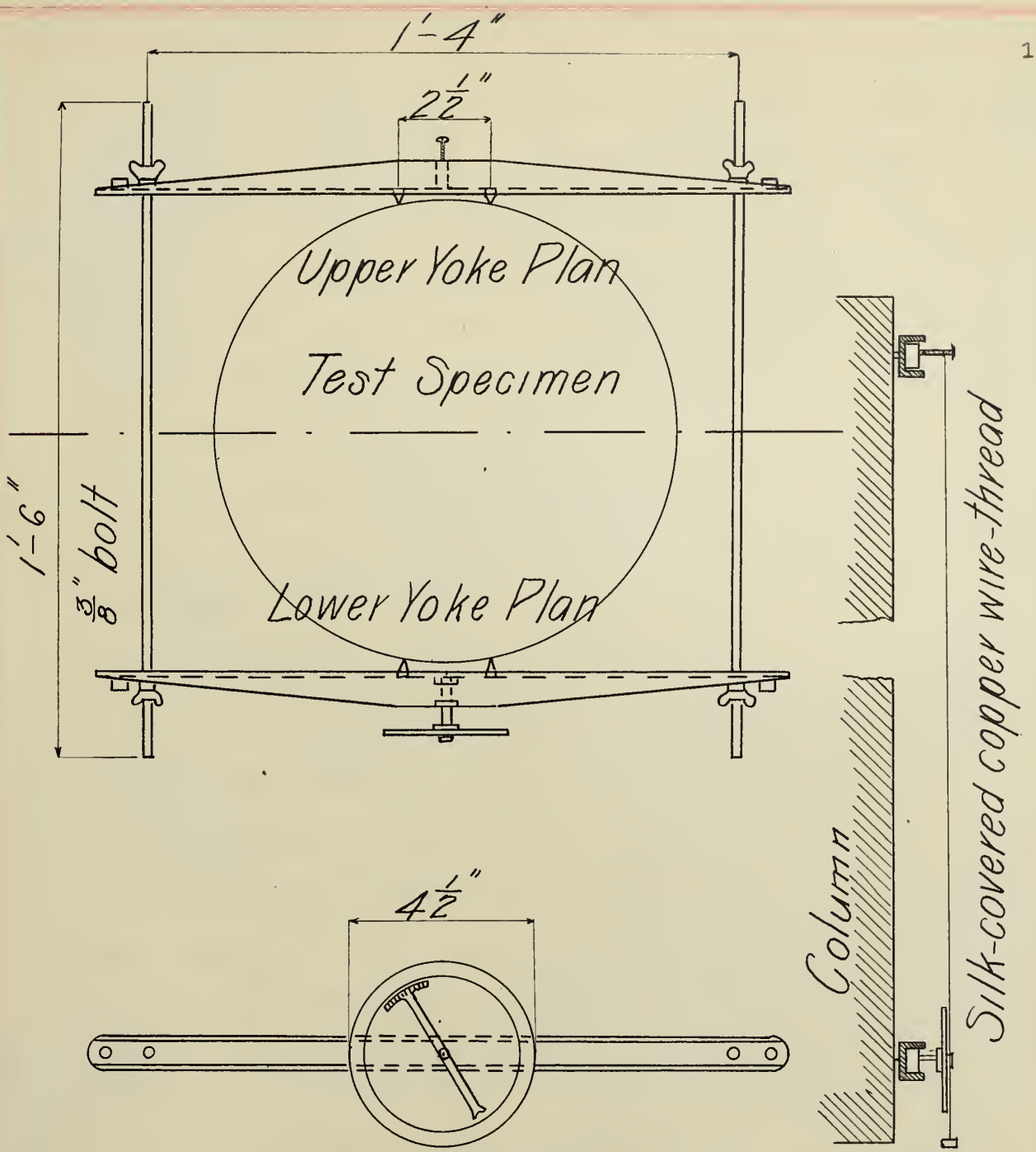
View showing the longer columns in storage.

The forms are still in place on two of the columns.

METHOD OF TESTING.

HANDLING THE COLUMNS: The columns had to be moved from the room in which they were stored to the testing laboratory, a distance of about 1000 ft. In order to do this most of the columns had to be securely roded before being handled. They were then picked up by a hoist and carefully loaded onto a dray. From the dray they run into the testing machine on dollies and there uprighted by means of hand hoists or by using the moving head of the testing machine as a hoist. Care was taken that the bottom of the lower bearing plate and the platform of the testing machine were thoroughly clean so as to give a uniform bearing surface. The top of the column was centered in the testing machine. The rods were then removed and the upper bearing block carefully centered over the top of the column.

EXTENSOMETERS: A modified form of the Johnson extensometer was used to measure the longitudinal deformations. They were arranged around the column at 90° to each other. Figure 2 is a detailed drawing of the extensometers and the yokes used for fastening them to the column. Their arrangement is also shown to better advantage in photograph page 69 . The yokes were placed at approximately equal distances from the top and bottom of the column. The guage length or distance between the centers of the yokes varied according to the length of the column.



Lower Yoke Elevation

Extensometer

Fig. 2

The pointer of the extensometer was moved by means of a silk-covered copper wire, which passed around a pulley in the center of the dial and was held taut by a weight tied to its lower end. By means of a vernier at the end of the pointer the deformations could be read to 0.0002 in. The method of operating the extensometers by means of a fine silk-covered copper wire proved very satisfactory.

The diameters of the columns recorded are the mean values of at least ten measurements taken at different points along the length.

LOADS: An initial load of about 95 lb. per sq. in. was put upon the column and the deformation readings taken, using that load as zero deformation. The loads were usually applied in increments of about 250 lb. per sq. in. on the column. The testing machine was stopped for each increment of load while the instruments were being read. The rate of application of the load was 0.05 in. per minute for columns 5 and 10 ft. long and 0.10 in. per minute for the longer columns.

STRESS-DEFORMATION DIAGRAMS.

METHOD OF CALCULATIONS FOR STRESS-DEFORMATION CURVES.

The method of calculations for the stress-deformation diagrams was as follows:

(A) Unit Stress In Columns.

Let P= total load on the column.

A= total cross-section of the column. For the column having spiral reinforcement the diameter was measured from the center to center of spirals.

f= Unit load on columns.

Then from Mechanics

$$f = \frac{P}{A}$$

This formula was used in calculating the unit stress on all columns.

(B) Stress in Longitudinal Steel.

Let e = total shortening in steel.

l = total length of longitudinal rods taken.

E_s = Modulus of elasticity of steel= 30,000,000 lb. per sq. in. the same as the column length.

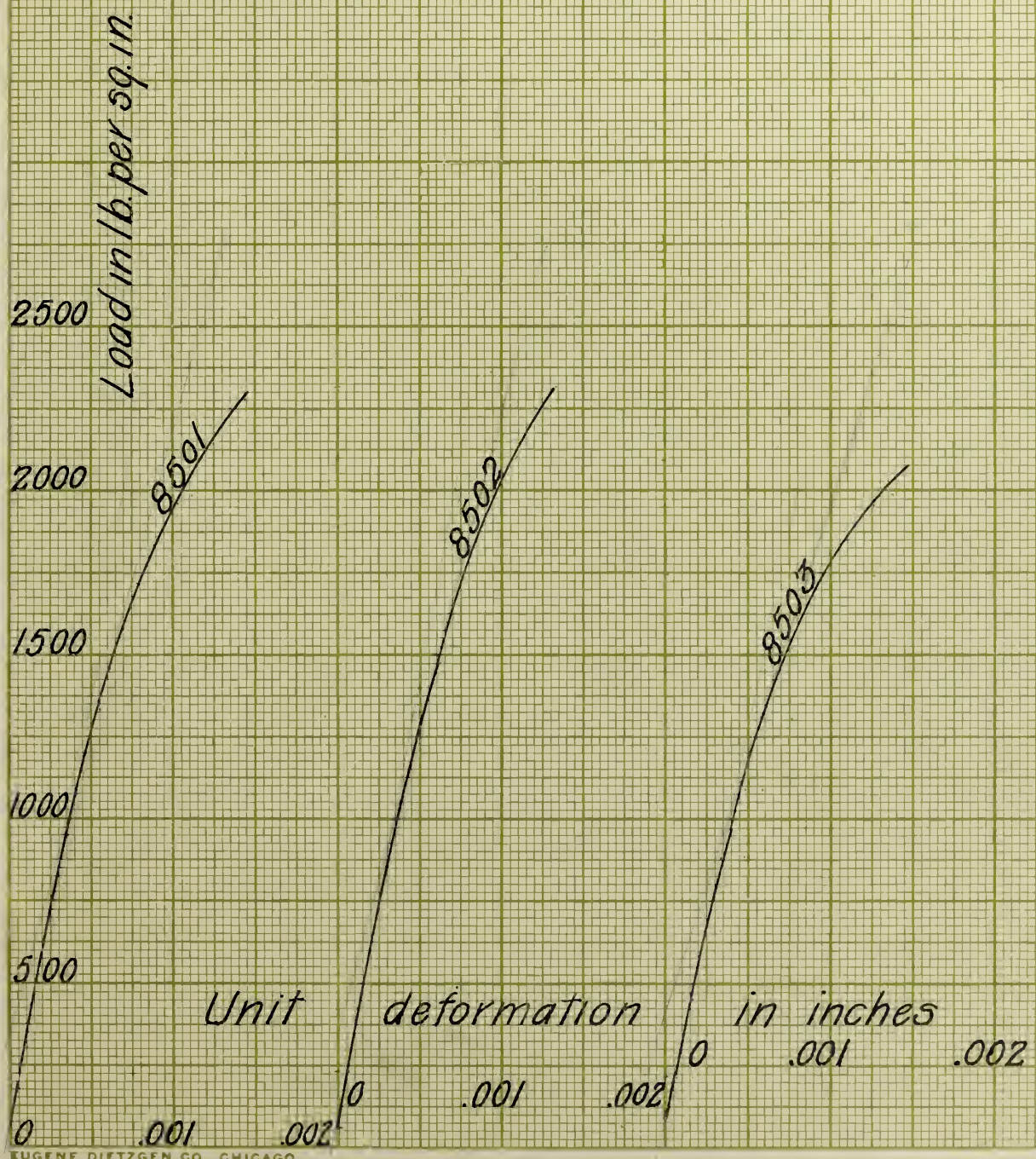
ϵ = Unit deformation.

$$\epsilon = \frac{e}{l}$$

The unit stress (f_s) in the steel due to a unit shortening ϵ is

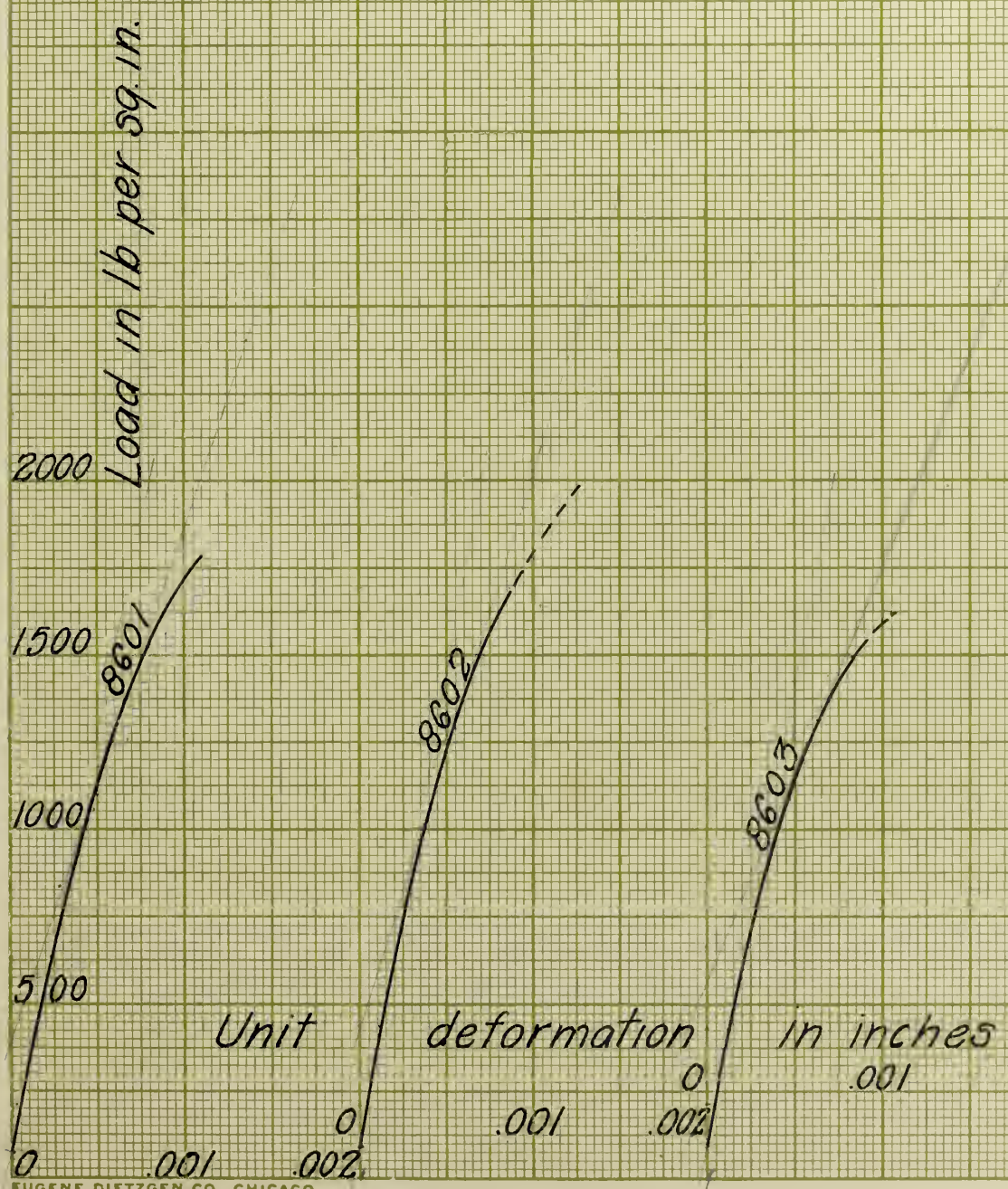
$$f_s = \epsilon E_s$$

Column	8501	8502	8503
Age: days	76	60	60
Length	5'-0"	4'-11½"	4'-11¾"
Ult. strength #/□in.	2360	2390	2096
Reinforcement		None	



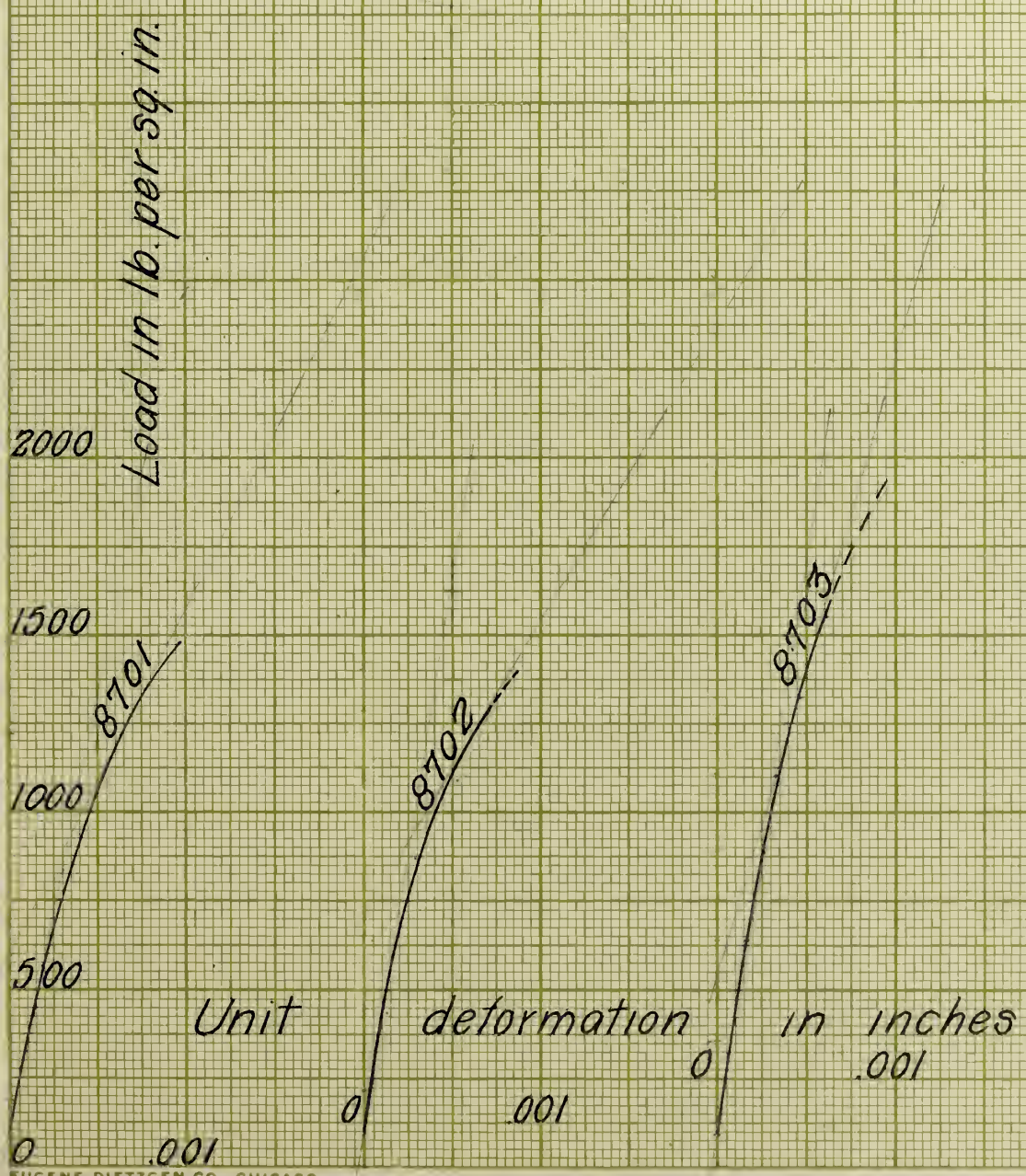
EUGENE DIETZGEN CO., CHICAGO.

Column	8601	8602	8603
Age: days	78	63	65
Length	10'-1"	10'-1¾"	10'-1"
Ult. strength #/□in.	1817	1970	1619
Reinforcement		None	



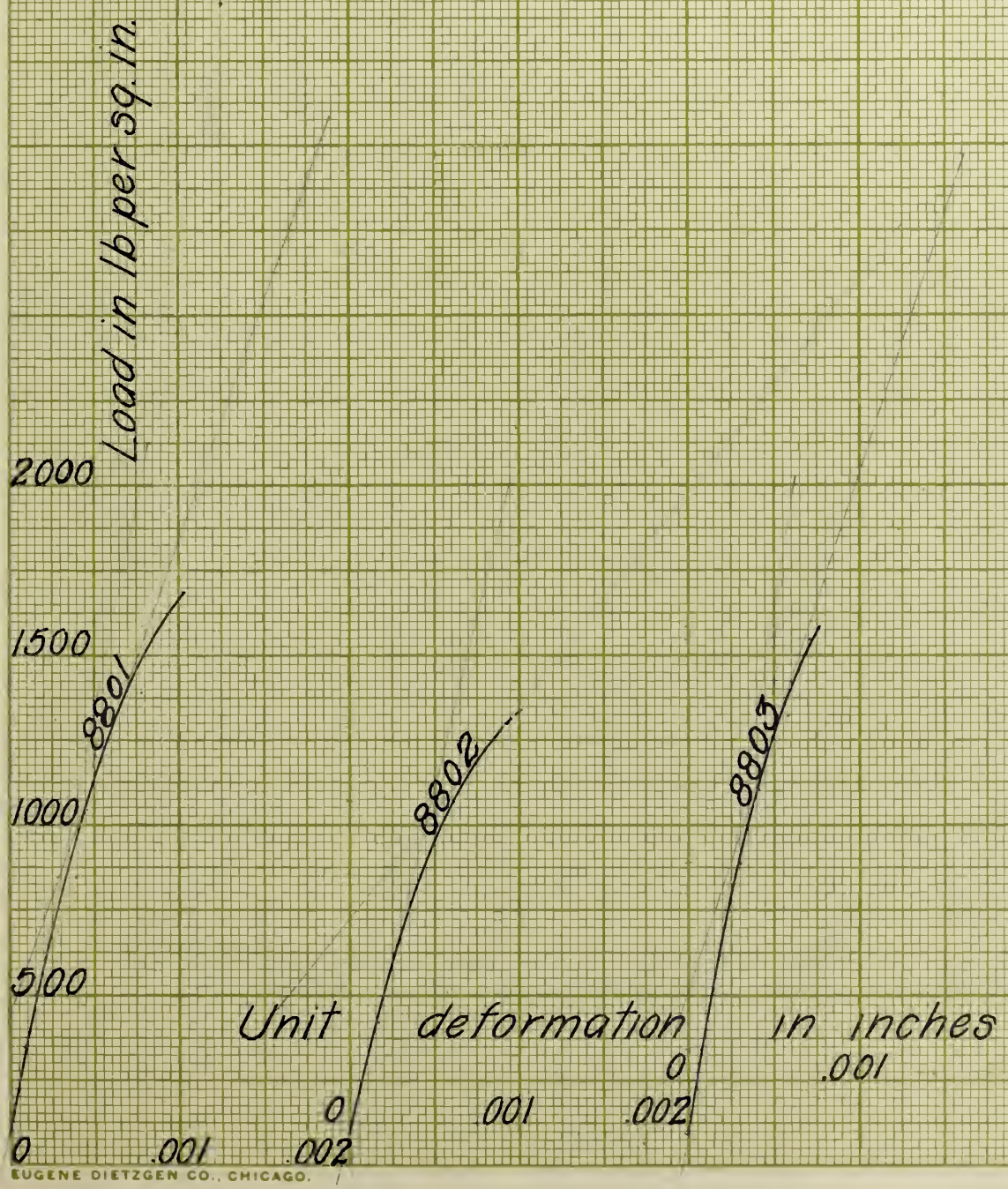
EUGENE DIETZGEN CO., CHICAGO.

Column	8701	8702	8703
Age: days	64	66	63
Length	14'-11½"	15'-0"	14'-7¼"
Ult. strength #/□in.	1480	1400	1935
Reinforcement	None		



EUGENE DIETZGEN CO., CHICAGO.

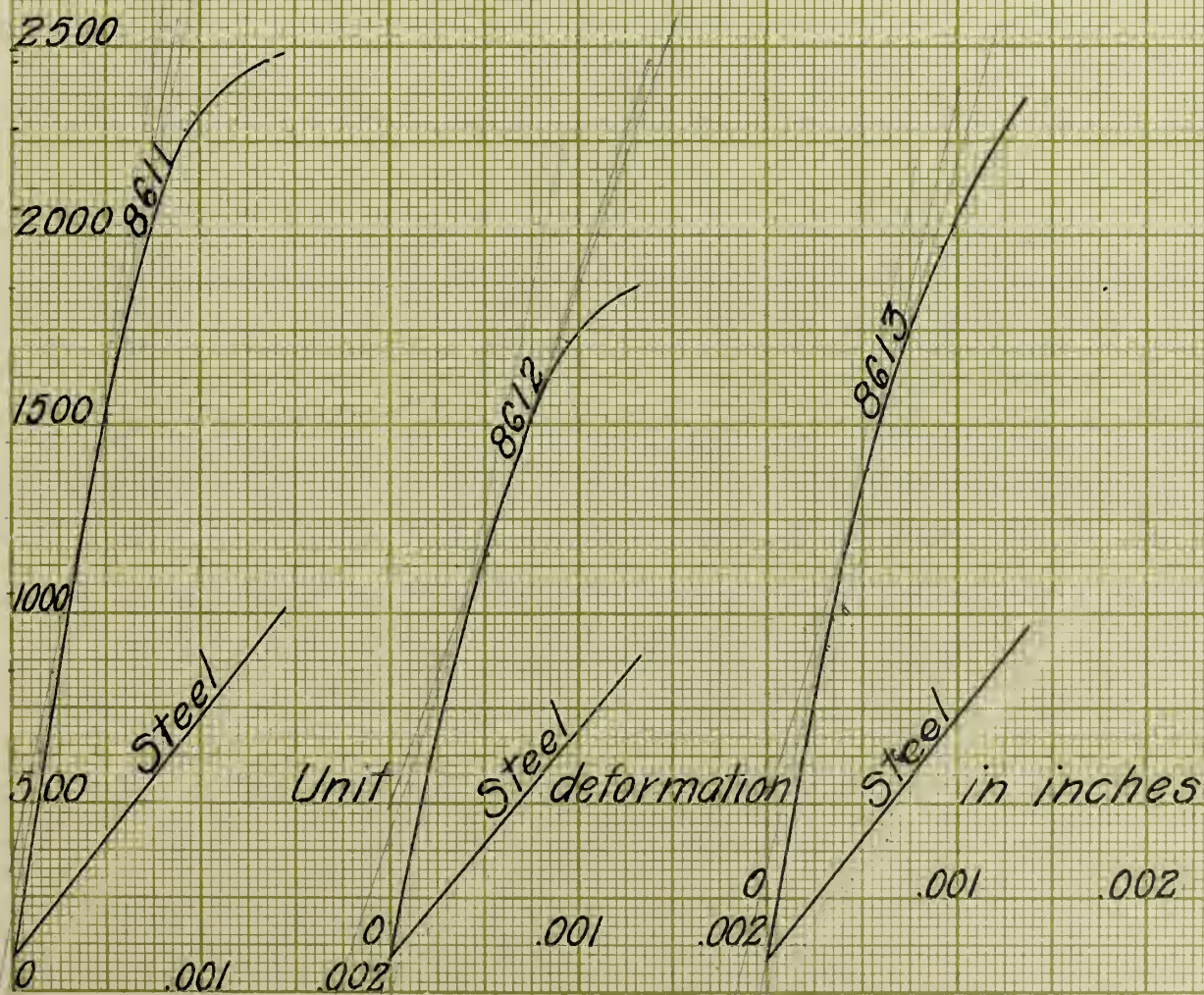
Column	8801	8802	8803
Age: days	64	65	64
Length	19'-6 5/8"	19'-3 1/8"	19'-5 1/2"
Ult. strength #/□in	1740	1330	1580
Reinforcement	None		



EUGENE DIETZGEN CO., CHICAGO.

Column	8611	8612	8613
Age days	63	66	63
Length	10'-0¾"	10'-0¼"	10'-0"
Ult. strength	2490	1870	2360
Reinforcement %	2.20	2.03	2.09

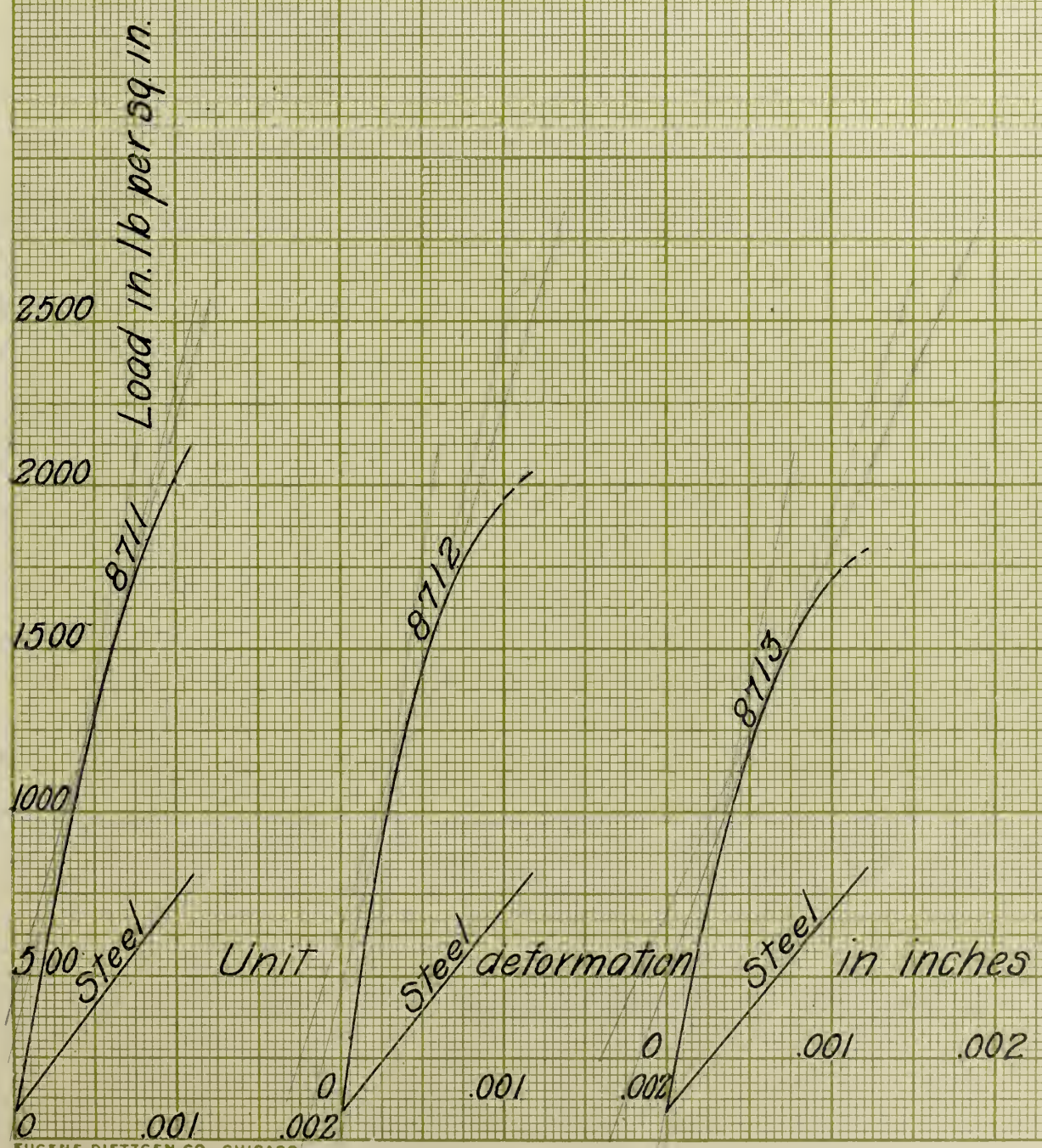
All reinforcement 6-¾" rods inside a 10" circle



EUGENE DIETZGEN CO., CHICAGO.

Column	8711	8712	8713
Age days	60	69	64
Length	14'-11 3/8"	14'-11 5/8"	14'-11"
Ult. strength #/□in	2100	2043	1805
Reinforcement %	2.23	2.06	2.06

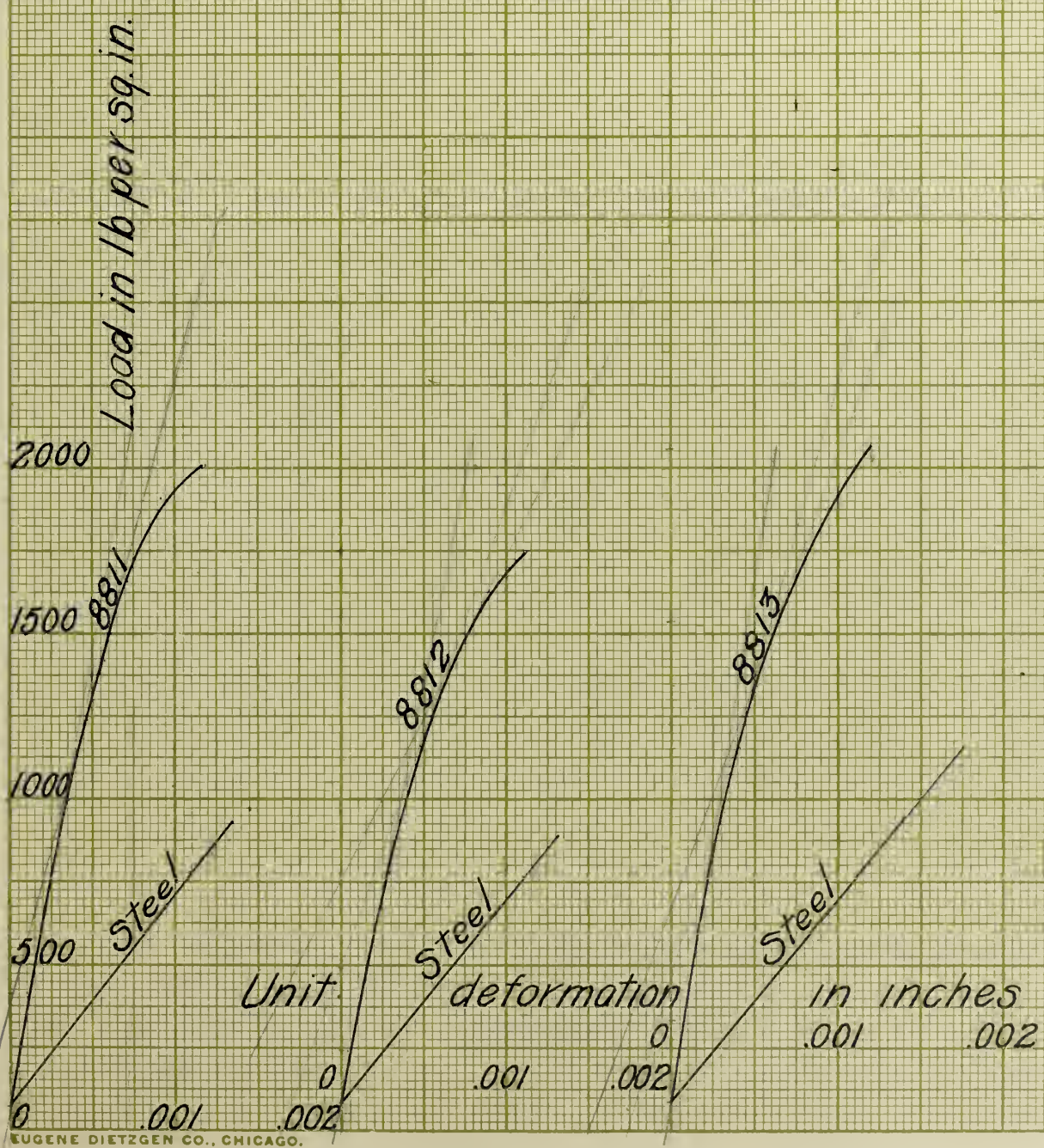
All reinforcement 6 - 3/4" round rods inside a 10" circle



EUGENE DIETZGEN CO., CHICAGO.

Column	8811	8812	8813
Age: days	62	65	65
Length	19'-7"	19'-6 3/8"	19'-6 5/8"
Ult. strength #/□in.	2010	1750	2060
Reinforcement %	2.20	2.06	2.03

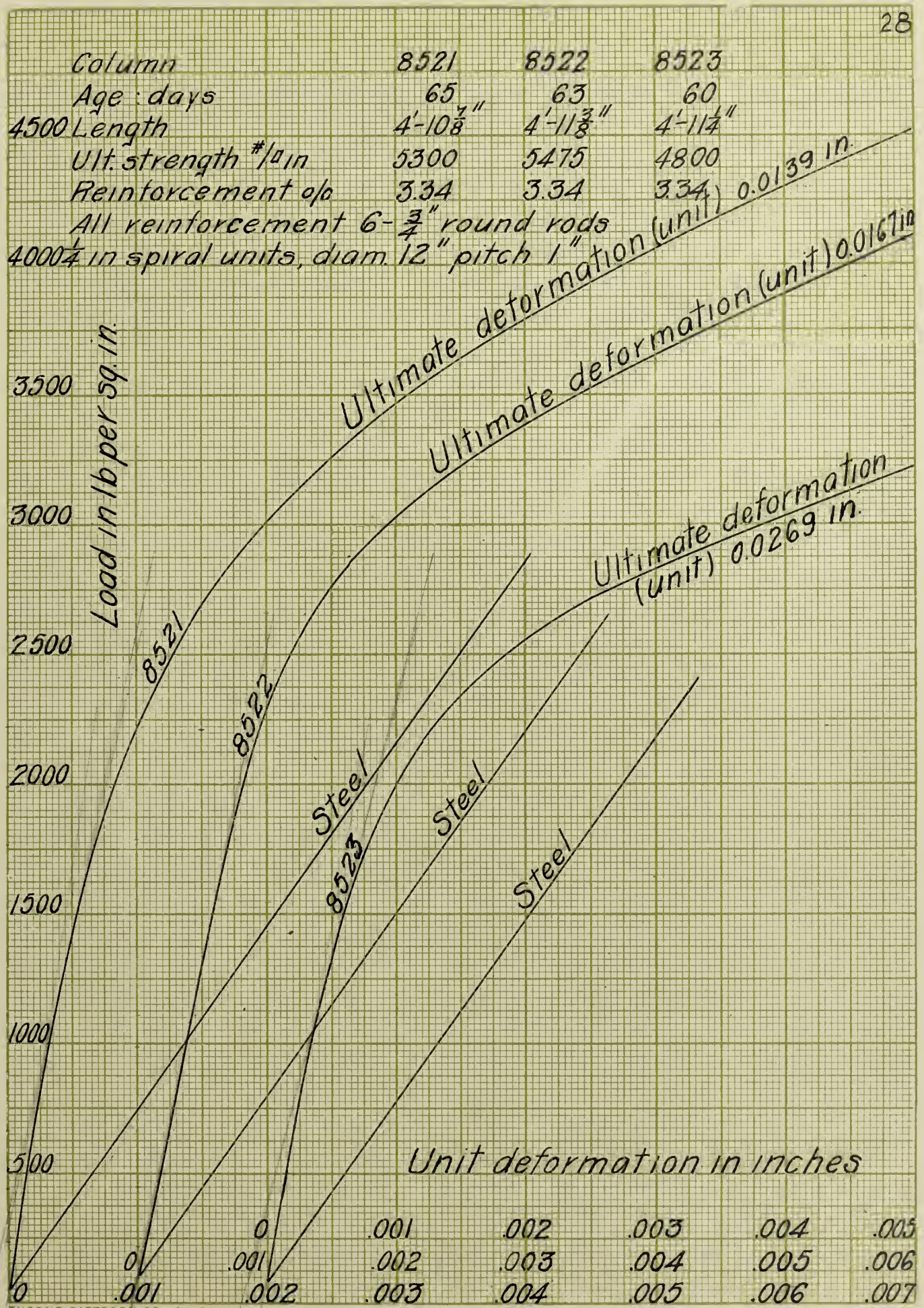
All reinforcement 6 - 3/4" round rods inside a 10" circle



EUGENE DIETZGEN CO., CHICAGO.

Column	8521	8522	8523
Age : days	65	63	60
Length	4'-10 7/8"	4'-11 3/8"	4'-11 1/4"
Ult. strength #/□in	5300	5475	4800
Reinforcement o/o	3.34	3.34	3.34

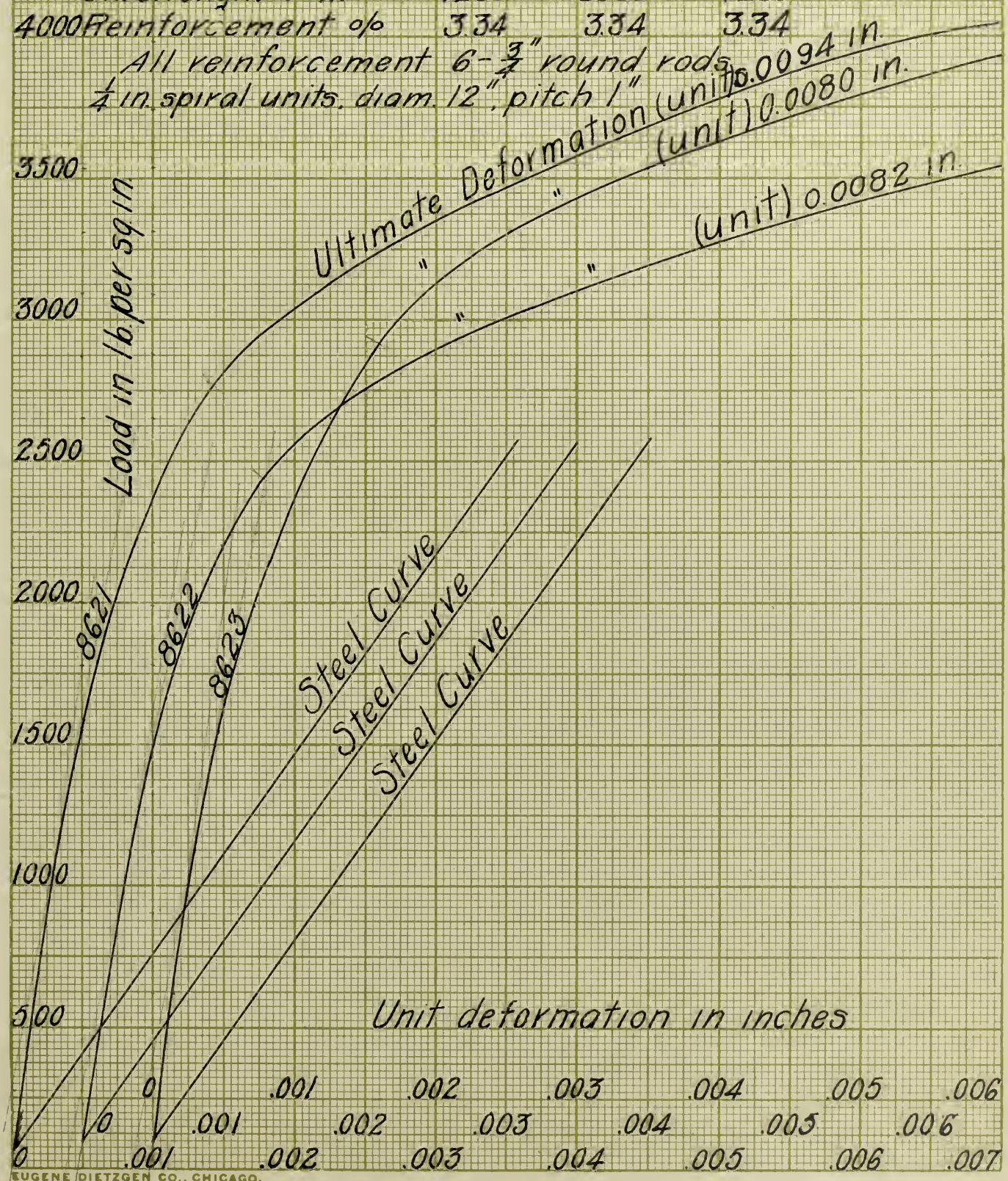
All reinforcement 6-3/4" round rods
1/4 in spiral units, diam. 12" pitch 1"



EUGENE DIETZGEN CO., CHICAGO.

Column	8621	8622	8623
Age: days	63	64	63
Length	10'-2 5/8"	10'-0 3/8"	10'-1 8/8"
Ult. strength #/□in	4260	3555	4230
Reinforcement o/o	3.34	3.34	3.34

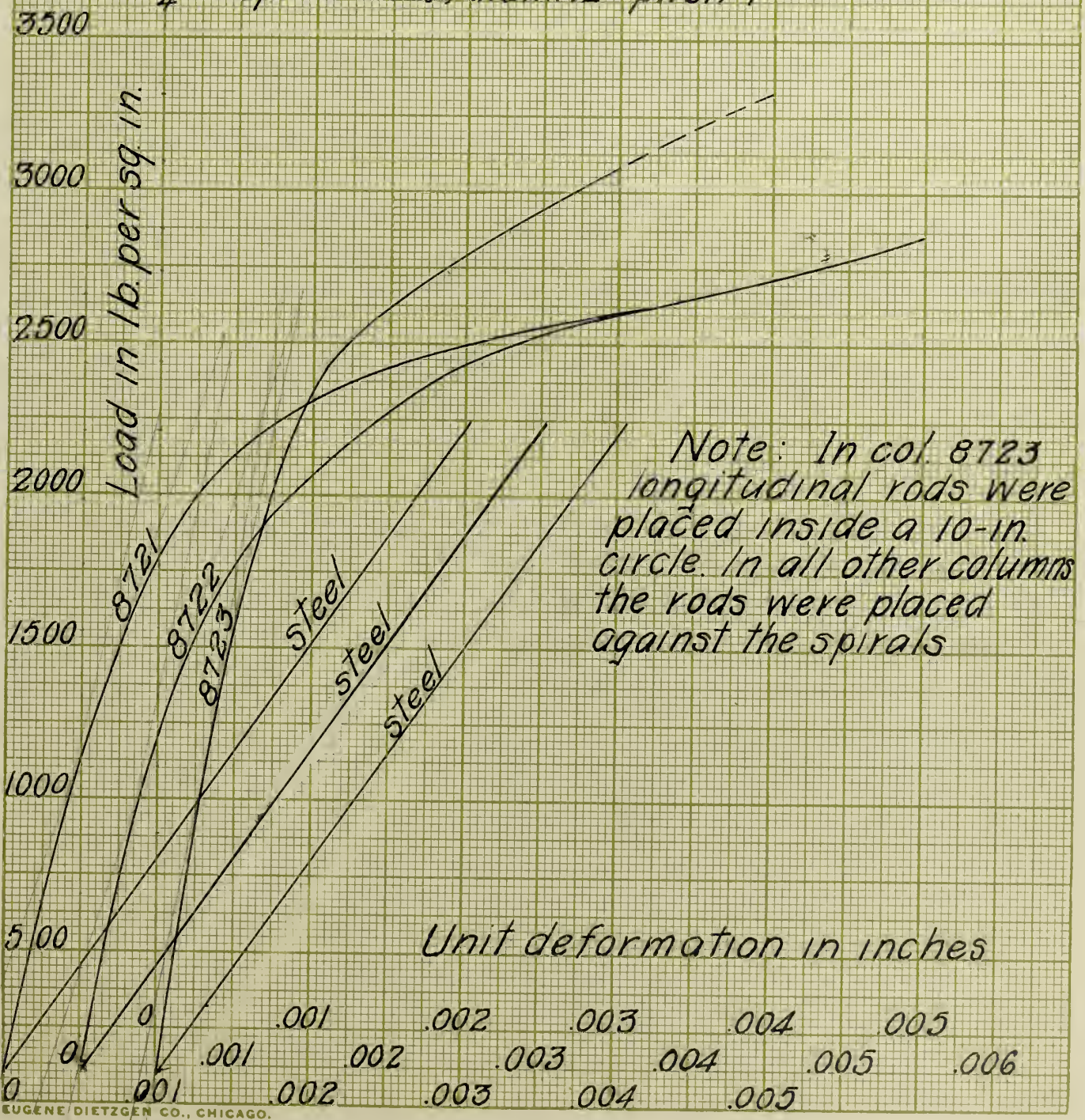
All reinforcement 6-3/4" round rods.
1/4 in. spiral units. diam. 12", pitch 1"



EUGENE DIETZGEN CO., CHICAGO.

Column	8721	8722	8723
Age: days	63	64	65
Length	14'-11½"	14'-11⅝"	14'-11½"
Ult. strength #/□in	2620	2874	3310
Reinforcement %	3.34	3.34	3.34

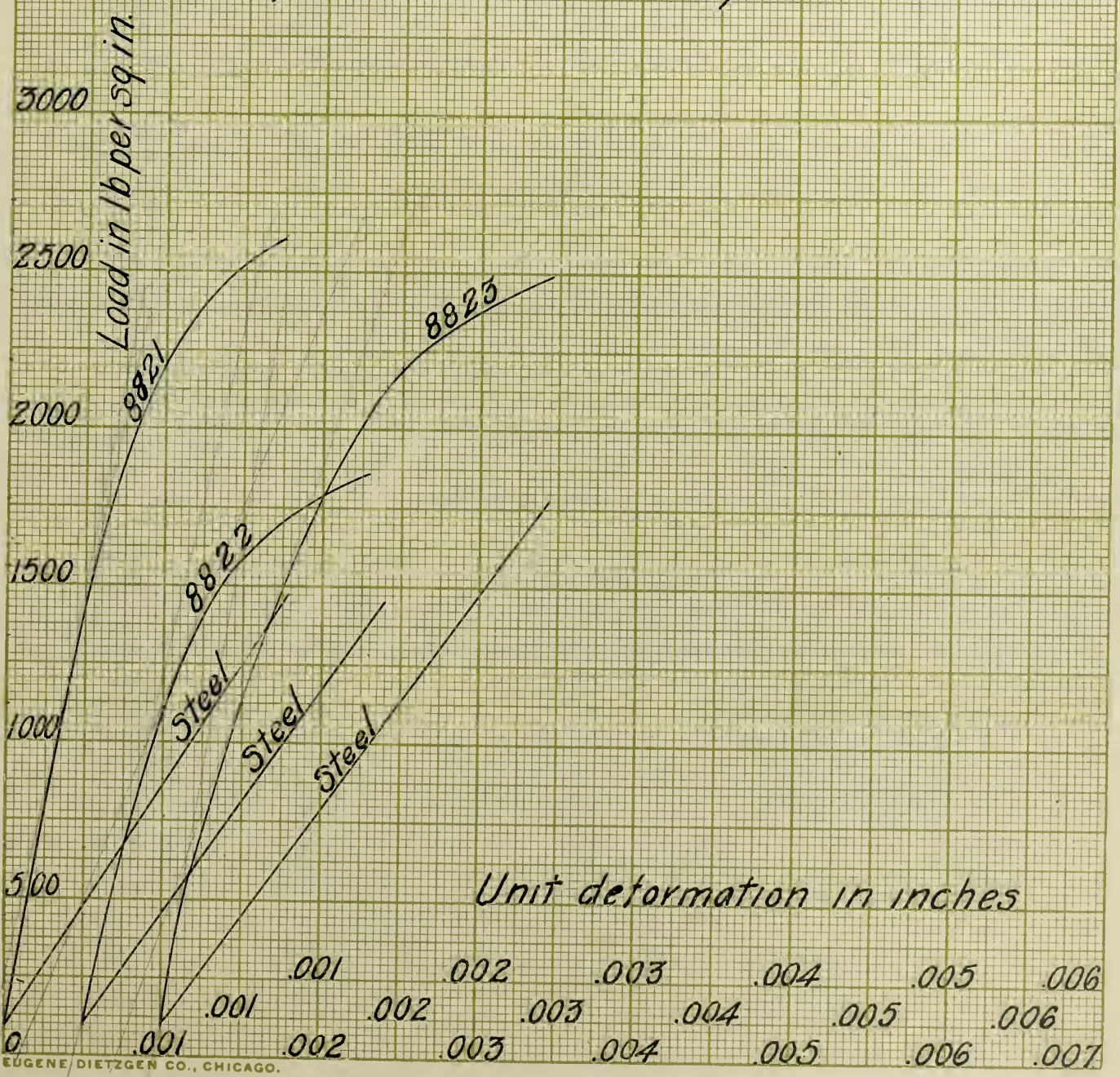
All reinforcement 6-¾" round rods
¼ in. spiral units, diam. 12" pitch 1"



EUGENE DIETZGEN CO., CHICAGO.

Column	8821	8822	8823
Age: days	64	66	63
Length	19'-7½"	19'-6½"	19'-6½"
Ult. strength #/□in	2720	1853	2720
Reinforcement o/o	3.34	3.34	3.34

All reinforcement 6-¾" round rods
¼ in spiral units, 12" diam, pitch 1"



EUGENE DIETZGEN CO., CHICAGO.

Column 8501

Load Lbs.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
8000	68	.00000	Age 76 days
20200	173	5	Reinforcement none
36100	309	10	Length 5' 0"
51100	438	13	Gauge 40"
66000	565	19	Diameter 12"
81300	696	24	Area 116.9 sq.in.
96300	825	29	
111500	956	35	
125700	1075	41	
141000	1209	47	
156000	1338	55	
170500	1460	62	
185000	1584	69	
200500	1718	77	
215000	1840	89	
230000	1970	103	
232400	1990	111	
250000	2140	125	
265000	2270	146	
275000	2360	171	Maximum

The maximum load was 2360 lb. per sq.in. The load fell off with increased shortening of the column and failure occurred at 1200 lb. per sq. in. by crushing at a section about 24 in. above bottom.

Column 8502

Load Lbs.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
6500	55	.00000	Age 60 days
27000	228	6	Reinforcement none
50000	421	12	Length 4' 11 1/2"
74000	624	20	Gauge 40"
99000	834	28	Diameter 12.3"
125000	1051	38	Area 118.8
150000	1262	49	
175000	1472	61	
200000	1683	73	
225000	1893	88	
250000	2105	107	
275000	2315	134	
284000	2390		Maximum

Column failed suddenly by crushing and diagonal shear from 8 in. to 2'ft from the top. The top of this column was 2 3/4 in. east of plumb. The column was straight.

Column 8516 made from same batch.

Column 8503

Load Lb.	Unit Load Lb. per. sq. in.	Unit Deformation in.	Remarks
11000	96	.00000	Age 60 days
25000	218	6	Reinforcement None
52000	452	16	Length 4' 11 3/4"
76000	660	23	Gauge 40"
101000	879	34	Diameter 12.1"
125000	1089	47	Area 115.0 sq. in.
150000	1304	59	
175000	1521	76	
200000	1740	96	
225000	1960	126	
241000	2096		Maximum

The column failed suddenly at 2096 lb. per sq. in. by diagonal shear and compression from 18 in. to 3 ft. from the bottom.

Column 8613 from batch.

Column 8601

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in	Remarks
8200	70	.00000	Age 78 days
25000	214	3	Reinforcement None
49000	420	13	Length 10' 1"
73200	626	23	Guage 100"
97800	837	26	Diameter 12.2"
123000	1051	49	Area 116.9 sq. in.
147000	1259	63	
177000	1520	80	
200000	1710	101	
212000	1817	148	Maximum

At the maximum load of 1817 lb. per sq. in. cracks appeared on the north east side. The column failed by diagonal shear and compression from 5 in. to 2 ft. from the base of the column.

The top of the column was 2 in. west of plumb.

Column 8602

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	94	.00000	Age 63 days
25000	214	4	Reinforcement None
51000	436	11	Length 10' 1 3/4"
75000	642	20	Gauge 100"
100000	856	30	Diameter 12.2"
124000	1061	41	Area 116.9 sq. in.
151000	1295	55	
175000	1500	68	
198000	1696	85	
230000	1970		Maximum

Column failed gradually at a load of 1970 lb. per sq. in. by shearing and splitting near the bottom.

Top of column was 2 1/4 in. out of plumb.

Column 8522 from same batch of concrete.

Column 8603

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	94	.00000	Age 65 days
25000	214	4	Reinforcement None
50000	428	12	Length 10' 1"
75000	641	23	Gauge 100"
101000	856	34	Diameter 12.2"
127000	1087	47	Area 116.9 sq.in.
151000	1291	62	
175000	1499	82	
189000	1619		Maximum

Top was 2 1/4 in. north of plumb.

Column failed by a gradual crushing about 2 ft. 6 in. from the bottom.

Column 8523 from same batch of concrete.

Cube tests seem to show that the concrete in this column was below the average.

Column 8702

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	96	.00000	Age 66 days
25000	218	4	Reinforcement None
50000	435	14	Length 15' 0"
75000	653	18	Guage 150"
100000	870	29	Diameter 12.1"
125000	1089	52	Area 115.0 sq. in.
148000	1289	70	
161000	1400		Maximum

Column was 2 1/2 in. North of plumb.

This column failed very gradually by a general crushing from 3 ft. to 5 ft. from the top.

Column 8701

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
10000	87	.00000	Age 64 days
20800	181	3	Reinforcement None
35800	312	8	Length 14' 11 1/2"
50100	436	13	Guage 150"
65500	570	19	Diameter 12.1
80900	705	25	Area 114.99 sq. in.
95500	832	31	
110400	963	44	
125000	1087	53	
140000	1220	64	
155000	1350	77	(ure)
170000	1480	98	No indication of fail-
170000			Maximum

The column was 3 1/2 north of plumb.

This column failed by a slow general crushing and splitting at about 2 ft. 4 in. from the top at 1480 lb. per sq. in.

Maximum deflection at center of column was 0.11 inches.

There was some indication that the failure was partly due to flexure.

Column 8703

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation	Remarks
11000	97	.00000	Age 63 days
40000	353	7	Reinforcement None
72000	636	17	Length 14' 7 1/4"
100000	883	26	Gauge 150"
125000	1105	33	Diameter 120"
150000	1325	48	Area 113.1 sq, in.
175000	1548	62	
219000	1935		Maximum

Top of column was 3/8 in. south of plumb.

This column failed suddenly by bursting and splitting from a point about 3 ft. above the base to the base. A loud report accompanied the failure.

Column 8801

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
10400	87	.00000	Age 64 days
21000	176	2	Reinforcement None
41000	345	8	Length 19 ft. 6 5/8 in.
61000	514	15	Gauge 200 in.
81000	681	28	Diameter 12.3 in.
100700	846	38	Area 118.8 sq. in.
124200	1045	45	
140400	1181	53	
155000	1304	60	
165500	1391	78	
188600	1588	87	
200000	1681	104	
207000	1740		Maximum

Top of Column was 1 3/4 in. Southeast of plumb. This column was very crooked and departed from a straight line about 1 1/4 in at several points in the upper 10 ft. of its length.

This column failed by a slow crushing and finally broke suddenly at the center. (See photograph)

Column 8802

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	84	.00000	Age 65 days
25000	214	5	Reinforcement None
50000	428	16	Length 19 ft. 3 1/8 in.
75000	642	27	Guage 200 in.
100000	856	42	Diameter 12.2 in.
125000	1070	61	Area 116.9 sq. in.
150000	1285	90	
155000	1330		Maximum

Top of column was 1 1/4 in south of plumb.

This column failed suddenly without warning by shear and crushing at a point about 3 ft. from the top. This sudden break also caused the column to snap at a point about 6 in.above the base. A later examination of the concrete at the point of failure showed that it was not of the same quality as the remainder of the column. This probably accounts for the low ultimate strength.

Column 8803

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	97	.00000	Age 64 days
39000	344	7	Reinforcement None
70000	618	18	Length 19 ft. 5 1/2 in.
100000	883	30	Guage 200 in.
125000	1104	41	Diameter 12.0 in.
150000	1325	58	Area 113.1 sq. in.
175000	1545	70	
180000	1580		Maximum

Top of column was 2 3/4 in. east of plumb.

This column failed by crushing at a point about 2 ft. 4 in. from the top at a break in the alignment of the column.

The uninjured part of the column was tested a second time. The column was cut to 14 ft. 11 in. and loaded continuously until failure occurred without taking any deformation readings.

This time failure took place about 2 ft. 4 in. from the top by crushing and splitting as in the first case. The maximum load was 217000 lb. or 1920 lb. per sq. in.

Column 8611

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	91	.00000	Age 63 days
25000	207	3	Reinforcement:Six
51000	243	9	3/4" round rods out-
76000	630	15	side a 9 in. circle.
102000	845	22	Length 10' 0 3/4"
127000	1050	30	Gauge 100"
151000	1250	38	Diameter 12.4"
176000	1455	46	Area 120.8 sq. in.
201000	1655	55	
225000	1865	64	
250000	2070	76	
275000	2280	92	(3 ft. from top).
297000	2460	136	Spalling and vertical cracks
300000	2490		

Top was 1 3/4 in. north west of plumb.

This column failed at load of 2490 lb. per sq. in.

Failure occurred gradually by compression and splitting from 3 ft. to 5 ft. 6 in. from the top. Vertical rods buckles outward at point of failure.

Column 8612

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	84	.00000	Age 66 days
25000	191	4	Reinforcement: Six
51000	390	11	3/4 in. rods inside a
76000	581	20	10" circle.
101000	774	29	Length 10' 1/4"
125000	956	39	Gauge 100"
151000	1156	51	Diameter 12.9"
175000	1340	62	Area 130.7 sq. in.
200000	1530	77	
225000	1720	94	
245000	1870	131	Maximum

Top 1 3/8 in. north east of plumb.

The column failed at a load of 1870 lb. per sq. in. by crushing of concrete and buckling of vertical rods from a point 3 ft. to the base.

Column made from same batch of concrete as 8512.

Column 8613

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	87	.00000	Age 63 days
31000	244	6	Reinforcement: Six
69000	545	15	3/4" rods outside a 9"
100000	790	25	circle.
125000*	987	35	Length 10' 0"
11000	87	4	Guage 100"
30000	237	9	Diameter 12.7"
63000	498	18	Area 126.7"
102000	806	29	
125000	987	35	
150000	1188	43	
175000	1384	53	
200000	1581	64	
226000	1784	77	
250000	1976	91	
275000	2177	112	
299000	2360		

*This load removed and the bearing block reset.

Top of column was about 1/4 in. east of plumb.
Column failed at load of 2360 lb. per sq. in. by crushing near bottom, extending upward about 2 1/2 ft.
Rods buckled at point of failure.
This column made from same batch of concrete as 8503.

Column 8711

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
10600	89	.00000	Age 60 days
21000	177	5	Reinforcement: Six
41000	346	11	3/4" round rods in a
59800	504	17	10" circle.
81000	683	14	Length 14' 11 3/8"
100000	842	31	Guage 150"
120000	1010	38	Diameter 12.3"
150700	1269	50	Area 118.8 sq. in.
171000	1440	59	
201000	1694	72	
220000	1853	81	
239000	2015	99	
249000	2100	112	Maximum

Column failed at a point 7 ft. above the base with local buckling of rods due to flexure.

Column split at bottom.

This column was crooked and bowed 2 5/8 in. at center.

Top was 1 7/8 in. west of plumb.

The tops of the rods were buried from 3/8 to 1/2 in. in the concrete.

Column 8712

Load Lb.	Unit Load Lb. per sq. in	Unit Deformation in.	Remarks
11000	86	.00000	Age 69 days
40000	311	5	Reinforcement: Six
70000	445	13	3/4" round rods in a
100000	777	21	10" circle.
127000	988	29	Length 14' 11 5/8"
150000	1168	38	Guage 150 "
175000	1360	48	Diameter 12.8"
200000	1555	59	Area 128.7 sq. in.
225000	1750	72	
250000	1944	99	
263000	2043		Maximum

Column failed by crushing and buckling of rods at a point about 2 ft. from bottom.

Top of column was 3 /8 in. west of plumb.

Column 8713

Load Lb.	Unit Load Lb. per sq. in	Unit Deformation in.	Remarks
11000	86	.00000	Age 64 days
36000	280	7	Reinforcement: Six
70000	545	17	3/4" rods in a 10"
100000	778	28	circle.
125000	973	37	Length 14' 11"
150000	1169	50	Gauge 150"
177000	1378	64	Diameter 12.8"
200000	1558	80	Area 128.7 sq. in.
225000	1750	107	
232000	1805	135	

Column failed near the middle. Vertical cracks about about 1 ft. long opened over the longitudinal rods. There were also some evidences of diagonal shear.

Column was rather crooked. A point 2 1/2 ft. below the top was 1 3/8 in. south east of plumb. The top was 1/2 in. north of plumb with reference to that point.

Column 8811

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in	Remarks
8500	70	.00000	Age 62 days
20300	170	3	Reinforcement: Six
50000	414	10	3/4" rods in a 10"
80000	663	21	circle
100200	830	28	Length 19' 7"
120000	995	35	Gauge 200"
150000	1242	48	Diameter 12.4"
171000*	1418	57	Area 120.8 sq. in.
200000	1658	71	
230000	1906	93	
242400	2010	118	Maximum

This column was rather crooked,owing to the crookedness the bearing block was set 1 1/8 in. to the south of the center of the column. This centered it over a section about 2 ft. 6 in. below the top.

The top was 4 3/4 in. north west of plumb and a section 5 1/2 ft. from the topwas 2 1/4 in. south of plumb.

Failure occurred at a section about 5 1/2 ft. below the top by buckling of the rods about 10 in. below a spacing band on the north side of the column. Cracks about 2 in. long appeared

about 5 1/2 ft. from the top where the angle in the column was observed. Vertical cracks appeared in the top 1 ft. of the column on the south side;showing a crushing in that part of the section due, probably, to eccentric loading. Tension cracks appeared on the south west side at the point of rupture.

*Vertical cracks spoken of above appeared at this load.

Column 8812

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	86	.00000	Age 65 days
32000	248	4	Reinforcement: Six
64000	497	15	3/4 in. rods in a
101000	785	29	10" circle.
125000	972	38	Length 19' 6 3/8"
150000	1166	48	Gauge 200"
175000	1360	64	Diameter 12.8"
200000	1555	83	Area 128.7 sq. in.
225000	1750	111	

Top of column was 2 3/8 in. north west of plumb.

Column failed suddenly about 5 ft. below the top. The failure was accompanied by a loud explosive report. Failure occurred by diagonal shearing, crushing and buckling of rods.

The restraining effect of the light bands on the vertical rods was shown in this failure.

Column 8813

Load Lb.	Unit Load Lb. per sq. in.	Unit Deformation	Remarks
11000	84	.00000	Age 65 days
40000	330	7	Reinforcement: Six
70000	536	15	3/4 in. round rods
101000	773	24	inside of 10" circle
125000	957	32	Length 19' 6 5/8".
150000	1150	41	Gauge 200"
175000	1340	51	Diameter 12.9"
200000	1530	64	Area 130.7 sq. in.
225000	1723	80	
250000	1914	100	
269000	2060		Maximum

Column failed by crushing and buckling near the middle. It.deflected until it was about 6 in. out of line at the center. Top of column was 1 1/4 in north of plumb.

Column 8523

Load lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	97	00000	Age 60 days.
26000	210	4	Reinforcement 1/4" spirals
52000	460	12	12" diam. pitch 1" six 3/4"
77000	680	21	rods.
100000	883	29	Length 4'-11 1/4"
175000	1104	38	Guage 40 inches.
150000	1325	49	Diameter 12.3
175000	1547	65	Area 113.1 c to c spirals.
201000	1775	79	
225000	1988	99	
250000	2210	126	
375000	2430	169	Spalling over spacing bands.
301000	2660	237	
325000	2870	318	
350000	3095	428	
375000	3315	571	
400000	3572	726	
425000	3760	904	
450000	3975	1100	
475000	4200	1331	
500000	4415	1618	
525000	4645	2040	
542000	4790	2689	
544000	4800		

After the maximum load was reached the load fell off.

The column had spalled badly on all sides.

Column 8603 from same batch.

Column 8521.

Load lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks.
6500	48	00000	Age 65 days.
26000	230	7	Reinforcement
50000	442	11	1/4" spiral 12" diam.
75000	663	19	Pitch 1" six 3/4" rods.
100000	885	26	Length 4'-10 7/8"
125000	1105	36	Guage 40"
150000	1326	45	Diameter 13" over all.
175000	1545	55	Area 113. 1" (12" c to c
200000	1769	67	spiral)
225000	1990	80	
252000	2225	104	
274000	2420	119	
300000	2650	145	
324000	2860	175	
350000	3090	212	Concrete over spacing bars
375000	3310	266	flaking off on all sides.
400000	3530	319	Spacing bars buckling at
425000	3750	394	several joints.
450000	3970	494	Concrete flaking over spirals.
477000	4300	616	Fine, vertical cracks.
500000	4420	718	
525000	4640	865	
550000	4860	1060	
575000	5080	1203	
600000	5300	1390	Test discontinued, column badly shattered, taking load very slowly.

Column 8522

Load lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	97	00000	Age 63 days.
25000	221	4	Reinforcement 1/4"
51000	450	11	spirals. 12" diameter
75000	662	19	pitch 1 in. six 3/4"
101000	982	27	round rods.
125000	1104	35	Length 4'-11 3/8"
151000	1333	45	Guage 40"
176000	1553	54	Diameter 12. over all
202000	1782	64	Area 113.1 c to c spi-
226000	2000	76	rals.
250000	2210	91	
276000	2440	106	
301000	2660	130	
325000	2870	163	Spalling over spacing
350000	3090	213	bands.
374000	3300	273	
300000	3525	350	
425000	3755	445	
455000	4020	563	
475000	4200	663	
500000	4415	781	
525000	4640	913	
550000	4860	1066	
575000	5080	1237	
600000	5300	1455	
620000	5475	1671	

Test was discontinued at 620000 lb. column taking load slowly. Column had spalled all over.

This column deflected about 0.1 in.

Column made from same batch as column 8602.

Column 8621.

Load lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
6900	66	00000	Age
30500	270	6	Reinforcement
61400	542	13	1/4" spiral 12" diam.
91700	810	22	Pitch 1" six 3/4" rods.
120000	1060	30	Length 10'-2 5/8"
150ooo	1326	40	Guage 100"
180000	1590	52	Diameter 12.4" over all.
210000	1856	65	Area 113.1 sq. In. inside
240000	2120	80	spirals (12" c-c)
470000	2384	98	
300000	2650	123	
330000	2915	169	
350000	3095	215	Spalling over spacing bars.
370000	3270	269	
390000	3445	368	
410000	3620	415	
430000	3800	511	Spalling all over.
450000	3975	619	
472000	4170	798	
482500	4260	935	Maximum

Top of column was 1 5/8 in. North West of plumb, otherwise the column was good and straight.

The first spalling at 2095 lb. per sq. in. occurred at three points of them being about 2 ft. from the top and bottom on the north side and the other in the centre of the column on the south side. This showed the column action of the reinforced concrete when encased in spirals and that it was acting as if it fixed at both ends.

Column 8622

Load lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	97	00000	Age 64 days.
26000	230	4	Reinforcement
52000	460	11	1/4" spiral 12" diam.
76000	671	17	Pitch 1" six 3/4" rods.
102000	910	26	Length 10'-0 3/8"
127000	1120	34	Guage 100"
151000	1333	44	Diameter 12.3"
176000	1555	54	Area 113.1 (12" in spiral)
201000	1775	63	
227000	2000	82	
250000	2210	99	Spalling over spacing bars
275000	2430	126	3" from top.
300000	2650	172	
325000	2870	258	
350000	3095	347	
375000	3310	481	
400000	3530	823	
402000	3555		

There was a maximum deflection of about 1 in.

Column 8C23.

Load lb.	Unit Load lb per sq. in.	Unit Deformation in.	Remarks
11000	97	00000	Age 63 days.
40000	354	7	Reinforcement
70000	619	15	1/4" spiral 12" diam.
102000	902	28	Pitch 1" six 3/4" rods.
127000	1121	30	Length 10'-1 1/8"
151000	1325	37	Guage 100"
175000	1547	46	Diameter 12.7" over all
201000	1777	59	Area 113.1 (12" in spiral)
225000	1988	72	
251000	2219	87	
275000	2430	106	
300000	2650	124	
325000	2872	154	Slight spalling over spacing
350000	3092	187	rods.
375000	3313	254	
400000	3535	350	
423000	3740	472	
450000	3980	642	
475000	4200	801	
479000	4230		

The column was in good alignment, but the top was about 1 in. north west of plumb.

There was a maximum deflection of about 3/4 in. to the south.

Six 3/4 in. rods were high carbon steel.

Column 8721.

Load lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	97	00000	Age 63 days.
28000	247	5	Reinforcement
51000	450	13	1/4" spiral 12" diam.
74000	654	23	Pitch 1" six 3/4" rods.
103000	910	37	Length 14'-11 1/2"
127000	1120	48	Guage 150"
151000	1335	64	Diameter 12.5"
175000	1545	78	Area 113.1 (12" in spiral)
200000	1768	96	
225000	1986	124	
250000	2210	165	Spalling over spacing rods.
275000	2430	262	
297000	2620	422	Maximum
285000	2520	471	
270000	2470	559	

Column was in good alignment but was 2 3/4 in. north of plumb.

During the test the top bearing block turned.

There was a maximum deflection at 2470 lb. per sq. in. was about 2 in. toward the west.

Column 8722.

Load lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	97	00000	Age 64 days.
25000	221	4	Reinforcement
50000	442	14	1/4" spiral 12" diam.
77000(	681	24	Pitch 1" six 3/4" rods.
101000	892	34	Length 14'-11 5/8"
125000	1105	47	Guage 150"
150000	1326	54	Diameter 12.3 over all.
175000	1547	74	Area 113.1 (12" in spiral)
200000	1768	95	Slight cracks and spalling
224000	1980	131	over spacing bars.
250000	2210	182	
275000	2430	249	
300000	2652	340	
325000	2874	477	Maximum

Top of column was 2 7/8 in. south east of plumb.

The column held 275000 lb when photograph was taken(p

Column 8723.

Load lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
11000	97	00000	Age 65 days.
40000	354	7	Reinforcement.
72000	635	11	1/4" spirals 12" diam.
100000	882	23	Pitch 1" six 3/4" rods.
125000	1104	31	Length 14'-11 1/2"
151000	1332	39	Guage 150"
176000	1553	49	Diameter 12.5" over all
200000	1767	60	Area 113.1 (12" c to c spiral)
226000	1996	74	
250000	2210	89	
275000	2428	118	Spalling over spacing bands.
300000	2730	188	
325000	2870	277	Vertical cracks around col.
350000	3090	301	
375000	3310		

Column failed by flexure.

Top was 1 3/4 in. north east of plumb.

Column 8821.

Load lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks
10000	88	00000	Age 64 days.
26000	230	4	Reinforcement
50000	441	11	1/4" spiral 12" diam.
75000	663	19	Pitch 1" six 3/4" rounds.
101000	892	29	Length 19'-7 1/2"
126000	1112	37	Guage 200"
151000	1332	47	Diameter 12.3 over all.
175000	1548	57	Area 113.1 (12" in spiral)
200000	1768	64	
226000	1996	82	
250000	2210	108	
275000	2430	137	
295000	2610	176	Spalling along spacing bars
308000	2720		on East side.
290000	2560	248	

Top of column was 1 3/4 in north west of plumb, the alignment was good. During the test the top bearing block turned.

Column 8822

Load lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks.
11000	97	00000	Age 66 days.
25000	221	5	Reinforcement
51000	450	15	1/4" spiral 12" diam.
75000	662	25	Pitch 1" six 3/4" rounds.
101000	982	39	Length 19'-6 1/2"
125000	1104	52	Guage 200"
150000	1324	69	Diameter 12.3" over all
175000	1545	91	Area 113.1 (c to c spiral)
200000	1768	142	
210000	1853	183	Maximum
190000	1680	210	

Top of column was 4 1/4 in. East of plumb. Column failed by flexure.

Column 8823.

Load lb.	Unit Load Lb. per sq. in.	Unit Deformation in.	Remarks.
11500	99	00000	Age 63 days.
29000	256	2	Reinforcement
53000	468	12	1/4" spiral 12" diam.
74000	654	22	Pitch 1" six 3/4" rods.
99500	879	34	Length 19'-61/2"
123000	1087	47	Diameter 12.4" over all
148000	1309	62	Guage 200"
174000	1538	78	Area 113.1 (12" c to c spiral)
199000	1759	95	Cracks appear over spacing bands.
223000	1970	116	Spacing bands bulge.
248000	2190	146	
275000	2430	210	
282000	2490	244	Maximum

Top of column is 1 1/8 in. south west of plumb. Column was in good alignment.

Column failed by flexure.

DISCUSSION OF TESTS AND DATA.

DISCUSSION OF COLUMN TESTS:

Plain Concrete Columns: The 5-ft. plain concrete columns failed at an average unit stress of 2282 lb. per sq. in. with a maximum variation of about 8% from the mean. Failure took place by diagonal shearing and crushing of the concrete. The first sign of failure was the dropping off of the load and an increased shortening of the column. Column 8501 held a unit load of 2360 lb. per sq. in. while the instruments were being read, and then, when the loading was continued, an increased shortening took place rapidly, and the column failed by slow crushing, accompanied by a slight bulging of the concrete at the point of failure. This failure is quite typical of a crushing failure and was observed in many of the plain columns.

The 10-ft. plain columns failed at an average unit stress of 1775 lb. per sq. in. with a maxium variation of about 9% from the mean value. Each of these columns failed by diagonal shear and a splitting of the column from the base upward. In every case failure began about 2 1/2 ft, from the bottom and sheared on an angle of about 60 degrees with horizontal. The Photograph Page 55, shows a typical failure of diagonal shear.

Plain Column No. 8601

Failure by Diagonal shear.

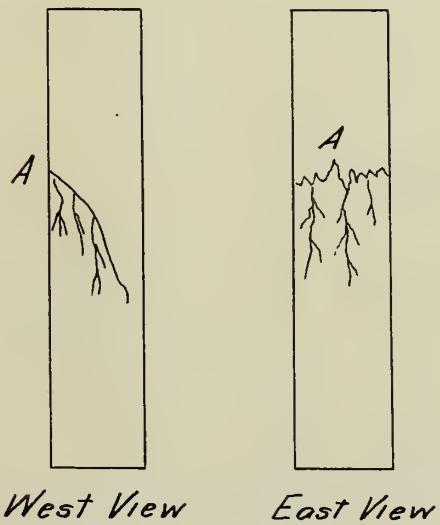
Max. Load 1817 lb. per sq. in.

View showing Column 8801 after Failure.

Typical failure for long columns of plain concrete.

20-ft. long. Max. load 1740 lb. per Sq. in.

The 15-ft. plain columns failed at an average unit stress of 1605 lb. per sq. in. with a variation of about 20% from the average. Two of these columns failed in the upper quarter and one in the lower quarter. Each of these columns failed in a different manner. Column 8701 failed by a slow, general crushing and splitting of the concrete about 2 1/4 ft. from the top at a the natural point of contra flexure in a longitudinal column. There was some indications that the failure here was due at least partly to flexure.



Column 8701
Figure 3

Figure 3 is a sketch of the column just before final rupture. The first sign of failure was a slight crushing of the concrete at point A. This was followed immediately by a splitting of the concrete as shown. The modulus of elasticity for the concrete at this point may have been as low as 1,500,000 or even 1,000,000 lb. per sq. in. just before failure. With such a low modulus a very small amount of bending would cause the concrete to crush and split as shown. Column 8702 failed gradually at 1400 lb. per sq. in. by a general crushing of the concrete as in the short column described above. In this case the failure was not accompanied by any marked increase in deformation. Column 8703

failed at about 3 ft. from the base by a sudden bursting and splitting of the concrete. This failure was accompanied by a loud report.

The 20-ft. plain columns failed at an average ~~and~~ stress of 1550 lb. per sq. in. with a variation from the mean value of 14 %. The failure of these columns was due largely to flexure . The points of failure (see data sheets) were at about the natural points of inflection or at the centre where a higher stress was caused by the columns' deflection. As an illustration of this phenomonon, a brief discussion of column action will be taken up at this point.

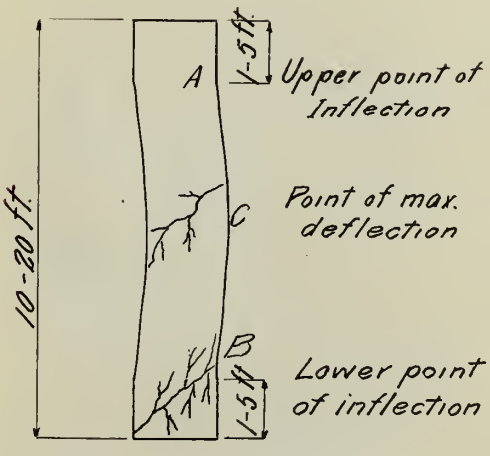
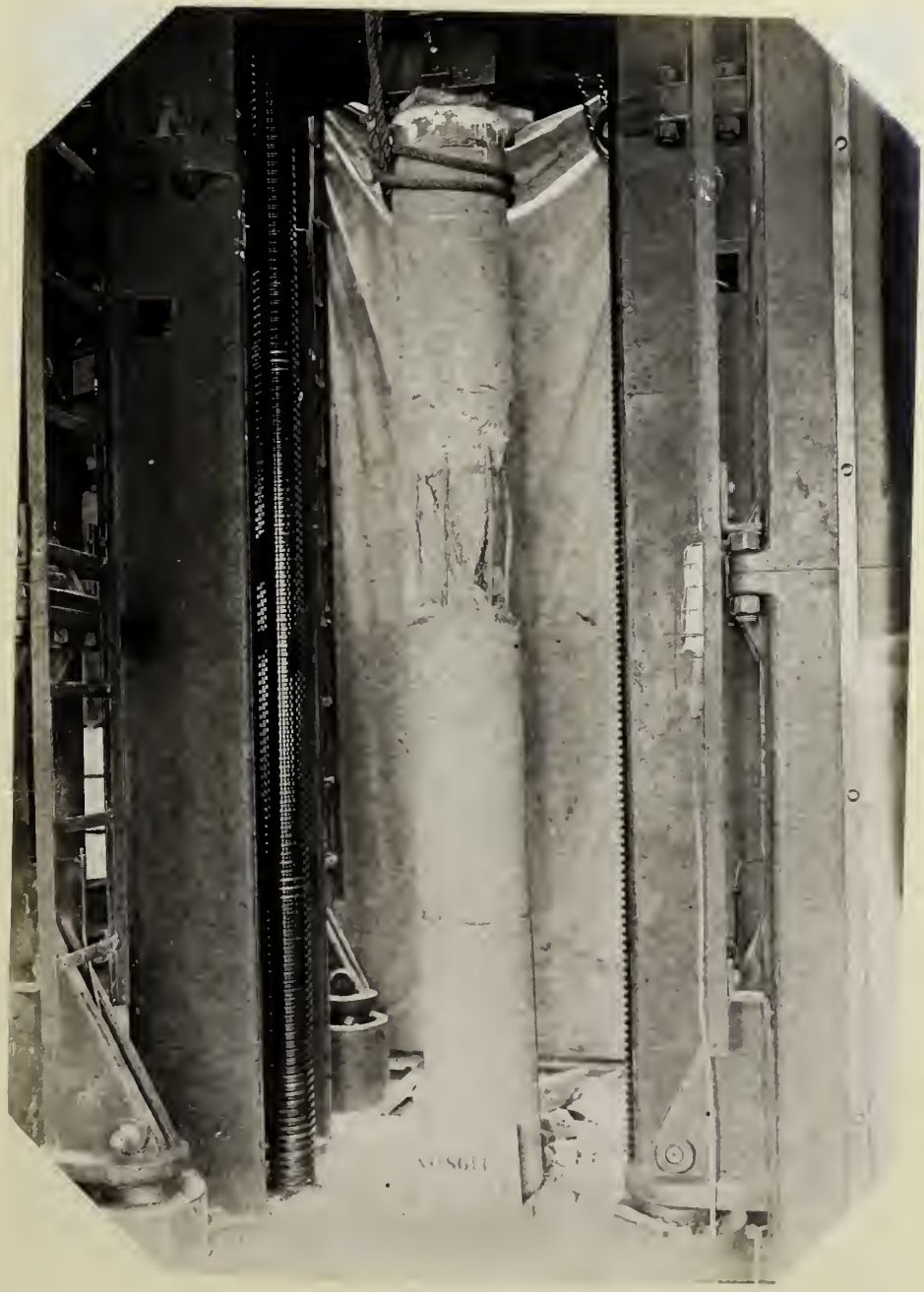


Fig. 4

Figure 4 is a typical diagram of the action of a column under axial load. The figure shows the column to be acting with both ends fixed. Note the similarity of action of the reinforced columns shown in the photograph Pages 61 and 67 to that of the figure. It is possible that the action of a plain concrete column with fixed ends is the same as that illustrated, by the fact that the point of rupture of the columns having a length of 10 diameters is usually located at one of the three points A, B, or C and that the modulus of elasticity at time of failure is often as low as 1,300,000 per sq. in. These points are clearly points when the stress in the



Failure of Column 8611, by gradual compression
and
buckling of rods.

10-ft. long. Max. Load 2400 lb. per Sq.in.

concrete is higher than it is at the intermediate sections and it is natural to suppose that the columns will ultimately fail at one of these places. The upper bearing block of the testing machine was made with a spherical joint which allowed some adjustment of the head to the action of the column. In two of the photographs pages 61 and 64 the movement of the upper bearing block is apparent and the column seems to be acting as if the upper end were hinged or at least partially hinged.

Columns reinforced with Longitudinal Rods only: The 10-ft. longitudinally reinforced columns failed at an average unit stress of 2240 lb. per sq. in. with a variation of about 16 % from the mean. All these columns failed by a gradual crushing and splitting of the concrete. Just before the maximum load was reached for the columns reinforced with vertical rods only, fine cracks appeared over the rods, and at the same time the concrete began to crush. This was followed immediately by a buckling of the rods and a splitting of the concrete in the vicinity of the buckling. The photograph of Column 8611, Page 59 shows such a failure. This failure seems to be due almost entirely to direct compression although there is evidence that diagonal shear had some effect. This photograph also shows that the bands which were used to hold the rods in place and also the bands which were used to hold the forms to the proper diameter may have exerted some influence upon the strength, since the crushing of the concrete and the buckling of the rods is limited to that part of the column which lies between these

View showing Column 8711 after failure by crushing due to flexure.

15-ft. long. Max. Load 2100 lb. per Sq. in.

spacing bands.

The 15-ft. longitudinally reinforced columns failed at an average unit stress of 1983 lb. per sq. in. with a variation of 7% from the mean. Two of these columns 8711 and 8713 failed near the center, the failures being due to the bending of the column as shown in the photograph of Column 8711, Page 61 The other 15- ft. column No. 8712 failed by general crushing of the concrete and buckling of the rods at a point about 2 ft. from the base.

The 20-ft. columns of this class failed at an average unit stress of 1940 lb. per sq. in. with a variation of 10 % from the mean. Two of these columns failed about 5ft. below the top and one, Column 8813 (shown in photograph, Page 64) near the middle. Failure in the first two was by general crushing accompanied by a buckling of the rods on all sides of the column. In one of these, Column 8812, the failure was accompanied by a loud report. A close viewof the failure of this column is shown in the photograph, Page

COLUMNS REINFORCED BY BOTH LONGITUDINAL RODS AND SPIRAL - HOOPING:

The strength of two of the 5-ft. Columns (8521 and 8522) of this series over-taxed the capacity of the testing machine but were pretty well shattered when the test was discontinued at 5300 and 5475 lb. per sq. in. respectively. Column 8523 reached its maximum strength at 4800 lb. per sq. in. The photograph Page

Column 8812.

Close view showing Buckling of Longitudinal Rods.

Note the spacing bands for the forms and rods.

Column 20-ft. long. Max. Load 1750 lb. per Sq. in.

Column 8813.

View showing buckling of Longitudinal Rods.

Note spacing Band just above and just below point of Failure. 20-ft. long. Max.Load 2060 lb. per Sq. in.

Columns 8521 and 8523

Two columns after the test.

Note spalling over spiralling.

Columns 5-ft. long.

59, shows columns 8521 and 8523 after the test.

Column 8723 was 1 5/8" out of plumb and the general character of the concrete, as indicated by the cube test, was of a poor quality so the concrete in this column could not have been up to the standard of the other columns. The first sign of failure was in the spalling of the concrete over the vertical spacing bands over the spirals. This was due to the buckling of the spacing bands and occurred at about 2000 to 2500 lb. per sq. in. or a little earlier. These cracks over the spacing bands appeared on all sides of the column at the same time and the cracks were well distributed up and down the length of the column, except perhaps a portion, for a foot or so in length at the top and bottom. As the load was applied the deformation increased rapidly and the concrete began to spall over the spacing bands. At a stress of about 2500 to 3000 lb. per sq. in. fine vertical cracks appeared around the body of the column indicating that the stress in the spirals was beyond the elastic limit. As the load was increased the shortening increased more rapidly than ever until the concrete flaked over the spirals (4000 lb. per sq. in.). The flaking increased as the load was applied. These columns deflected about 0.10" at time of maximum load.

The 10-ft. column of this class failed at an average unit stress of 4015 lb. per sq. in. with a variation of 11% from the mean. Failure in these columns occurred by flexure. The point of maximum deflection from a straight line was usually near the

View of Column 8621 after test.

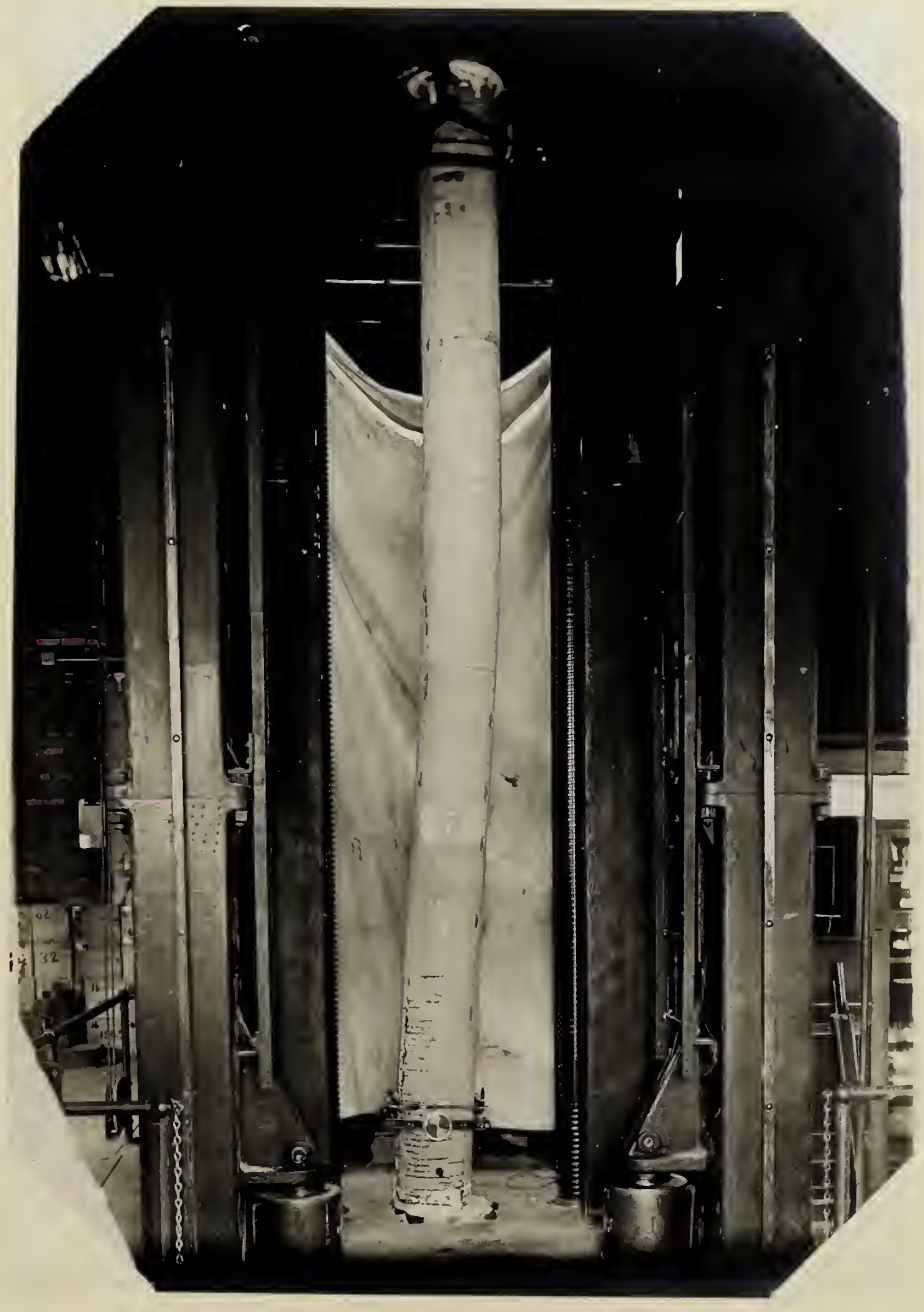
Note the shape of the Column. The photograph shows that the column acted as if both ends were fixed.

Column 10-ft. long. Max. Load 4260 lb. per sq. in.

centre.

The column action was most marked in Column 8621. The first spalling occurred simultaneously at three points on the spacing bands at a unit stress of about 2100 lb. per sq. in. as shown at A, B and C on Photograph of column 8621, Page 67. This column acted as if it were fixed at both ends, Columns 8622 and 8623 failed in the same general manner as 8621, the deflection at the centre for the maximum load was about 1 in. The indications of distress were the same as for all other spirally-hooped columns. Note that column 8623 had high carbon steel rods which took no more stress than the mild steel rods of Column 8721.

The 15-ft. Columns of this class stood a unit stress of 2885 lb. per sq. in. with a variation of 15% from the average value. Failure took place by flexure in the same general manner as in the 10ft. columns. The deflection at maximum load was about 2 in. or twice that of the 10ft. columns. Column 8723 had the longitudinal rods placed in side a 10in. circle the same as for the longitudinal reinforced columns, instead of having them in contact with the inner surface of the spirals. This column stood a unit stress of 536 lb. per sq. in. more than either column 8721 or 8722. This additional strength may be due to the restraining effect of the spacing bands or to the restraining effect of the concrete itself, or to the better opportunity for band between the rods and the concrete, or to a combination of these causes.



Column 8722.

Failure by flexure.

Column 15-ft. long. Max. Load 2874 lb. per sq. in.

The arrangement of the extensometers on the column is shown.

The 20-ft. columns of this class stood a unit stress of 2354 lb. per sq. in. with a variation of 21% from the mean. All of these columns failed by flexure with an increase in deflection over that of the 15ft. columns. The top bearing block adjusted itself more easily to the bending movement in these longer columns. This probably reduced the ultimate strength of the column to some extent. These 20ft. columns and also the 10 and 15-ft. columns failed by flexure long before the concrete flaked on the body of the column.

The photograph of Column 8722, Page 69 shows the typical action of a long column reinforced with both spirals and longitudinal rods. This column stood a unit load of 1680 lb. per sq. in. while columns 8821 and 8823 took loads 2560 and 2490lb. per sq. in. each. Just why the ultimate strength of this column was so low, it is impossible to say.

Table 5.

INVESTIGATION OF EFFECT OF PLUMBNESS

Col. No.	Length Approx. ft.	Maximum Load lb. per sq. in.	Deflection, in.	Inches out of Plumb	Remarks on failure
8501	5	2360	——	——	Crushing 2 ft. from bottom to top
8502		2390	——	$2\frac{3}{4}$	Shearing $\frac{3}{4}$ ft. to 2 ft. from top
8503		2096	——	——	sudden shear and compression 2 ft. to $3\frac{1}{2}$ ft. from top.
8601	10	1817	——	2	Diagonal shear $\frac{1}{2}$ ft. to $2\frac{1}{4}$ ft. from bottom.
8602		1890	——	$2\frac{1}{4}$	Slow shear and splitting in bottom third
8603		1619	——	$2\frac{1}{4}$	Crushing and splitting $2\frac{1}{2}$ ft. from bottom to bottom.
8701	15	1480	.11	$3\frac{1}{2}$	Crushing due flexure. $12\frac{3}{4}$ ft. from base
8702		1400	.07	$2\frac{1}{2}$	Gradual crushing 3 ft. to 5ft from top
8703		1935	.10	3/8	Bulging with explosive report 3 ft. from bottom
8801	20	1740	.17	$1\frac{3}{4}$	Slow crushing 10 ft. from base.
8802		1330	.32	$1\frac{1}{4}$	Shear and crushing 2 ft. to 3 ft. from top
8803		1580	.20	$2\frac{3}{4}$	Crushing $2\frac{1}{4}$ ft. from top
8611	10	2490	——	$1\frac{3}{4}$	Bulging 3 ft. to $5\frac{1}{2}$ ft. from top
8612		1870	——	1 3/8	Crushing 3 ft. from bottom to base
8613		2360	——	$0\frac{1}{4}$	Crushing $2\frac{1}{2}$ ft. from bottom to base
8711	15	2100	.28	1 7/8	Pure flexure. Base split 7 ft. from bottom
8712		2043	.01	3 1/8	Crushing 2 ft. from bottom
8713		1805	.05	$0\frac{1}{2}$	Crushing with evidences of shear near center.
8811	20	2010	.92	$4\frac{3}{4}$	Flexure and splitting $5\frac{1}{2}$ ft. from top
8812		1750	.26	2 3/8	Sudden failure with explosive report 2 ft. to 5 ft. from top
8613		2060	.20	$1\frac{1}{4}$	Crushing near center

8813

8521	5	5300	——	Plumb	Did not reach maximum do.
8522		5475	——	"	
8523		4800	——	"	Flexure
8621	10	4260	1.62	1 5/8	Flexure
8622		3555	1.00+	——	"
8623		4230	.75	1	"
8721	15	2470	.80	$2\frac{3}{4}$	Flexure
8722		2874	.13+	2 7/8	"
8723		3310	.56	$1\frac{3}{4}$	"
8821	20	2720	1.68+	$1\frac{3}{4}$	Flexure
8822		1853	1.94	$4\frac{1}{4}$	"
8823		2490	1.16	1 1/8	"

EFFECT OF PLUMBNESS AND ALIGNMENT ON STRENGTH.

PLUMBNESS:

Table 5 gives among other things the list of columns, distance out of plumb and the ultimate load of the columns tested. From an inspection of the table it will be observed that the lack of plumbness may have caused the column to fail earlier than it would have failed if it had been plumb, but the figures do not show this conclusively. If any thing, they show that the plumbness of the column did not have anything to do with the ultimate strength. Take for instance Column 8711 and 8713; Column 8713 was only 1/2 in. out of plumb and sustained a load of only 1805 lb. per sq. in. while Columns 8711 and 8712 were 1 7/8 in. and 3 1/8 in. out of plumb and supported a load of 2100 and 2093 lb. per sq. in. respectively. There are also evidences that the plumbness did have a great influence upon the strength as in Column 8822 which was 4 1/4in. out of plumb and sustained only 71% of the average load carried by Columns 8821 and 8823. From a further study of the table it can be said; not-with-standing some of the striking facts to the contrary; that the plumbness of a column did exert some influence upon the strength but just how much loss of strength was due to the lack of plumbness and how much to other causes, it is impossible to say. Many of the plain columns were bowed and crooked in addition to being out of plumb. Nearly all of the plain columns failed at joints where the columns angled.

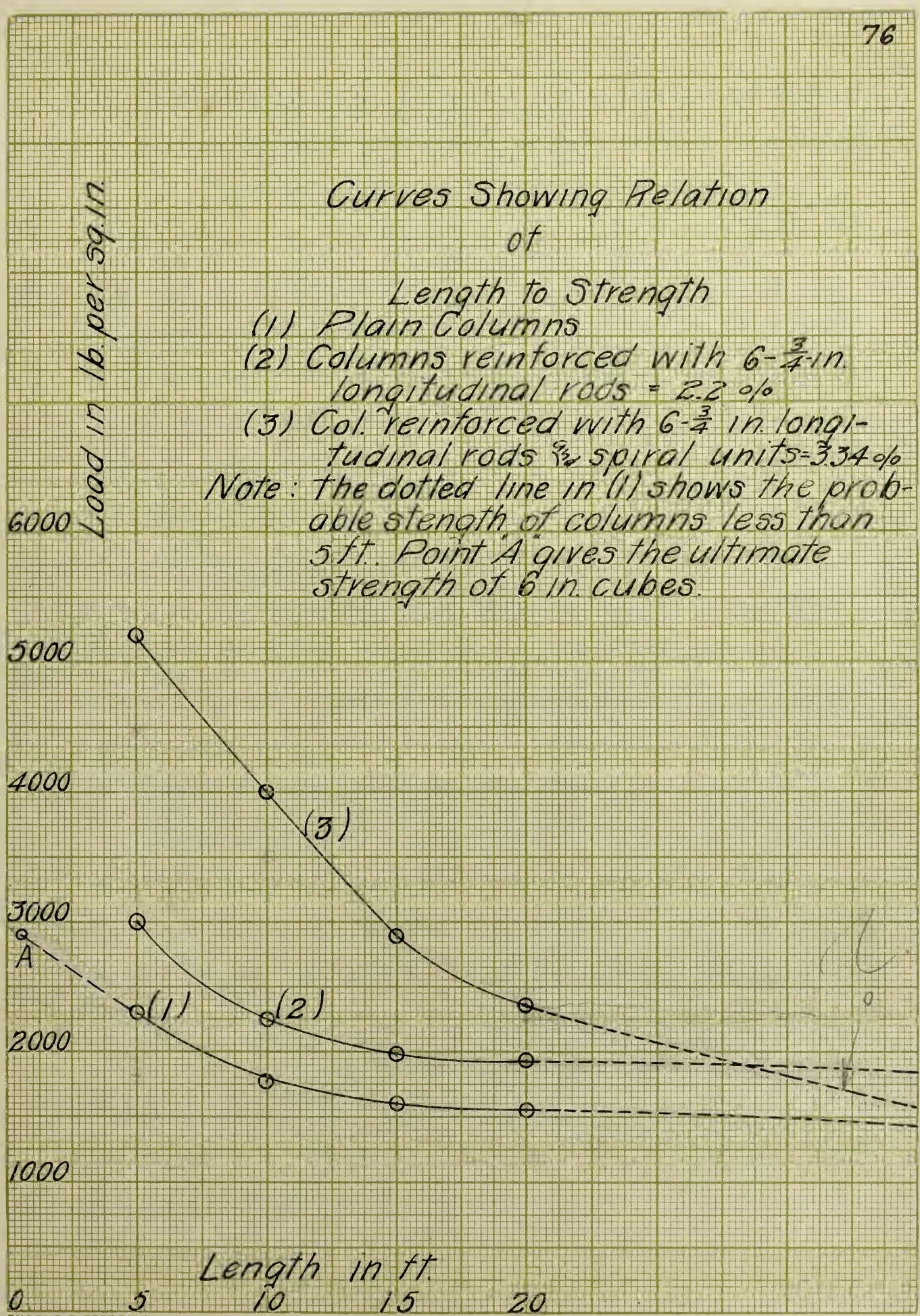
Whether or not they sustained a lower load, than they would have if they had been straight, is not known. But since the failure occurred in every case, except one, by direct compression or shear the crookedness could not have exerted much influence upon the strength.

EFFECTIVENESS OF REINFORCEMENT.

COLUMNS REINFORCED WITH LONGITUDINAL RODS ONLY: A study of the curves Page 64 shows that the reinforcement strengthens the columns very materially. The increase in strength gained by using 2.2% (6 3/4-in. rounds) longitudinal rods is about constant for columns of lengths between 10 and 20-ft. This difference amounts to about 400 lb. per sq. in. or about 182 lb. per sq. in. for 1 % of reinforcement. If the stress in the longitudinal steel, taken as calulated by the unit deformation of the steel as given in the data of the tests, be compared with the load which the tests show that the steel carried, it will be observed, that, the steel, in the 10-ft. longitudinally reinforced columns, carried a load of 565 lb. per sq. in. Whereas the calculated load which the steel should have carried was 900 lb. per sq. in. The load which the calculations show that the steel carried in the 15 and 20-ft. longitudinally reinforced columns was 750 and 800 lb. per sq. in. respectively, while the actual load carried was 378 and 390 lb. per sq. in. This discrepancy may be due to the fact that the steel was covered by a small amount of plaster of paris at the upper end and thus the deformation in the column and in the steel

were not the same. Many tests of longitudinally reinforced columns have proven that longitudinal steel is most effective when it bears directly upon the bearing plates. The longitudinal rods would therefore have been more efficient if they had had a bearing upon the upper bearing plate instead of having been covered at the top by a thin layer plaster of paris. Tests of two 5-ft. columns reinforced with six 1-in. round rods 3.8%) by Mr. D. Q. McComb tends to show that for columns of this length there is an increase in the efficiency of such reinforcement over that for the longer columns. However, a higher percentage of reinforcement was used in these two columns and the large bars probably gave additional stiffness to the columns. Besides, it was necessary to reduce the stress for this reinforcement on the basis of the amount of reinforcement used in the main series of tests, which also altered conditions. It is probable then that Mr. McComb's tests give values that are too high.

Therefore, it can be said that the increased strength gained by using six 3/4-in. longitudinal bars only as reinforcement is practically constant for columns between 5 and 20-ft. and that the increase in strength of a 5-ft. over a 20-ft. column is due to the shorter length and not to the reinforcement.



EUGENE DIETZGEN CO., CHICAGO.

COLUMNS REINFORCED WITH SPIRALS AND LONGITUDINAL RODS:

The reinforcement consisting of both 6-3/4-in. longitudinal rods and spiral units adds greatly to the strength in the shorter columns and its effectiveness grows rapidly less as the length of the column increases. For a 20-ft. column the spiralling alone adds about 350 lb. per sq. in. per 1 % of steel to the strength; for a 5-ft. column it adds about 1930 lb. per sq. in. per 1 % of steel. Thus it is seen that the increase in strength of the 5-ft. column appears to be due to the increased efficiency of this style of reinforcing for the shorter lengths; but a further study of the test data and the load-deformation diagrams shows that the increased efficiency for the shorter lengths is due to the greater deformation that may be developed in the shorter columns before the flexure materially reduces their strength.

EFFECT OF LENGTH-RATIO UPON STRENGTH:

GENERAL : It has, up to within the last two years, been a quite generally accepted fact that the length up to 20 or 25 diameters has very little influence on the strength of a reinforced concrete column. It is now generally recognized that lengths up to 10 or 12 diameters have no appreciable effect upon the strength of columns. The series of tests on plain and reinforced columns taken up in this thesis show that the length is a very important factor of the strength.

PLAIN COLUMNS: The average ultimate strength of the plain concrete columns varied from 1550 lb. per sq. in. in a 20-ft. column to 2282 lb. per sq. in. for a 5-ft. column and increased to 2900 lb. per sq. in. for the 6-in. cubes. These points are plotted, Page 76 , taking the unit load as ordinates and the column length ratio as abscissae. Note that if the curve is extended from the 5-ft. column to the 6-in. cube that the decrease seems to be according to the same law as the increase from the 20-ft. to 5-ft. columns. A 5-ft. column has an increase in strength 50 % over that for a 20- ft. column and an increase in strength of 30% over the 10-ft. column.

COLUMNS REINFORCED WITH LONGITUDINAL RODS ONLY: The curve representing the relation of the length to the strength of longitudinally reinforced columns resembles in form the corresponding curve for the plain columns. The position for the ultimate strength of the 5-ft. columns if this class was estimated from three 5-ft. column tests, 8511, 8512, and 8513, made by Mr. D. A. McComb, 1910. These columns were reinforced with about 3.8 % of steel instead of 2.2 % steel for those in the tests reported in this thesis. This curve resembles the curve for the plain concrete columns. The stress in the steel remained about the same no matterwhat the length of column. From the curve it will be noted that a 5-ft. column reinforced with longitudinal rods only is about 60 % stronger than a 20-ft. column and about 33 % stronger than a 10-ft. column.

COLUMNS REINFORCED WITH BOTH LONGITUDNAL RODS AND SPIRALS:

The curve representing the relation of length to strength for this class of columns is considerably different from the curve of the plain columns. In this case a 5-ft. column was about 120 % stronger than the 20-ft. column and 93 % stronger than the 10-ft Columns. If we continue the curve for the spirally reinforced columns until it meets the curve for the plain column produced it will be noticed that a column about 36 ft. long and reinforced with both spirals and longitudinal rods would have about the same strength as a plain column of the same length. However, one can scarcely draw definite conclusions regarding 36-ft. columns from the results of tests of columns 5 to 20-ft. long.

The three curves shown on Page 76 are plotted from an analagous series of tests; Curve (1) for plain columns, curve (2) for columns reinforced with longitudinal rods only and curve (3) for columns reinforced with both spirals and longitudinal rods. The ordinate between curves (1) and (2) will give the stress in the longitudinal rods and the ordinate between curves (2) and (3) will be a measure of the load taken by the spirals. Then, by dividing the stresses by the per cent reinforcement the result will be the unit stress per 1 % of reinforcement. In the conclusions regarding the relation of length to strength of either plain or reinforced concrete columns, it seems that the length must be taken into account even for

columns 5 diameters in length. If the test specimens are 10-FT. columns, the unit load should be reduced for columns more than 10-ft. in length and for spirally reinforced columns a reduction of say, 58 % of the ultimate strength of a 10-ft. column would have to be made to get the strength of a 20-ft. column, and this would have to be increased 30 % to get the strength in a 5-ft. column.

SUMMARY OF COLUMN TESTS

Col No.	Length ft-in	Diameter in.	Age at Test days	Maximum Load Lb. per sq, in.	Average Lb.per sq. in.	Initial Modulus of Elasticity
			Reinforcement None			
8501	5-0	12.2	76	2360		2680000
8502	4-11 1/2	12.3	60	2390		2750000
8503	4-11 3/4	12.1	60	2096	2282	2400000
8601	10-1	12.2	78	1817		2500000
8602	10-1 3/4	12.2	63	1819		2750000
8603	10-1	12.2	65	1619	1775	3500000
8701	14-11 1/2	12.1	64	1480		2550000
8702	15-0	12.1	66	1400		3250000
8703	14-7 1/4	12.0	63	1935	1605	3250000
8801	19-6 5/8	12.3	64	1740		2500000
8802	19-3 1/8	12.2	65	1330		2100000
8803	19-5 1/2	12.0	64	1580	1550	2600000
			Reinforcement Six 3/4 in. Round Steel Rods.			
8611	10-0 3/4	12.4	63	2490		
8612	10-0 1/4	12.9	66	1870		
8613	10-0	12.7	63	2360	2240	
8711	14-11 3/8	12.3	60	2100		
8712	14-11 5/8	12.8	69	2043		
8713	14-11	12.8	64	1805	1983	
8811	19-7	12.4	62	2010		
8812	19-6 3/8	12.8	65	1750		
8813	19-6 5/8	12.9	65	2060	1940	
			Reinforcement Six 3/4 in. Round Steel Rods and Spiral Units: Diameter 12 in.,pitch 1 in.,Spiral Wire 1/4 in. Diameter			
8521	4-10 5/8	12.0	65	5300*		
8522	4-11 3/8	12.0	63	5475*		
8523	4-11 1/4	12.0	60	4800	5192	
8621	10-2 5/8	12.0	63	4260		
8622	10-0 3/8	12.0	64	3555		
8623	10-1 1/8	12.0	63	4230	4015	
8721	14-11 1/2	12.0	63	2470		
8722	14-11 5/8	12.0	64	2874		
8723	14-11 1/2	12.0	65	3310	2885	
8821	19-7 1/2	12.0	64	2720		
8822	19-6 1/2	12.0	66	1853		
8823	19-6 1/2	12.0	63	2490	2354	

COMPARISON OF COLUMN TESTS WITH CUBE TESTS

Col. No.	Age at Test days	Length of Column ft.in.	Maximum Load Lb.per sq. in.	Age at Test days	Maximum Load Lb. per sq. in.	Average Load Lb. per sq. in.
8501	76	5-0	2360	122	3200	
					3085	
					2900	3062
8502	60	4-11½	2390	85	3580	
				86	3730	
				88	3190	3500
8503	60	4-11¾	2096	71	2095	
				71	2330	
				71	2375	2267
8601	78	10- 1	1817	122	3765	
				122	3960	
				122	3957	3894
8602	63	10- 1¾	1890	81	2980	
				81	2935	
				82	2685	2867
8603	65	10- 1	1619	74	2150	
				74	2500	
				74	2320	2323
8701	64	14-11½	1480	91	3272	
				91	3270	
				91	3300	3281
8702	66	15-0	1400	80	3170	
				80	2920	
				82	2950	3013
8703	63	14- 7¼	1935	61	2110	
				63	2330	
				65	2350	2263
8801	64	19-6 5/8	1740	111	2990	
				111	3620	
				111	3400	3337
8802	65	19-3 1/8	1330	77	2870	
				77	2642	
				77	2960	2857
8803	64	19- 5½	1580	71	2750	
				71	2455	
				71	2500	2568

COMPARISON OF COLUMN TESTS WITH CUBE TESTS

Col. No.	Age at Test days	Length of Column ft. in.	Maximum Load lb. per sq. in.	Age at Test days	Maximum Load lb. per sq. in.	Average Load lb. per sq. in.
8611	63	10– 0¾	2490	81	2455	
				81	2230	
				82	2435	2372
8612	66	10– 0¼	1870	90	2480	
				90	2170	
				90	2320	2323
8613	63	10– 0	2360	71	2095	
				71	2330	
				71	2375	2267
8711	60	14–11 3/8	2100	93	3860	
				93	3090	
				93	3410	3453
8712	69	14–11 5/8	2043	70	2290	
				70	2460	
				70	2660	2470
8713	64	14–11	1805	69	2710	
				69	2500	
				69	2635	2615
8811	62	19– 7	2010	96	2520	
				96	2920	
				96	2650	2698
8812	65	19– 6 3/8	1750	71	2540	
				71	2260	
				71	2522	2441
8813	65	19– 6 5/8	2060	63	2315	
					2425	
					2360	2367

COMPARISON OF COLUMN TESTS WITH CUBE TESTS

Col. No.	Age at Test days	Length of Column ft-in.	Maximum Load Lb. per sq. in.	Age at Test days	Maximum Load Lb. per sq. in.	Average Load Lb. per sq. in.
8521	65	4-10 5/8	5300	102	2725	
				102	2945	
				102	2505	2725
8522	63	4-11 3/8	5475	81	2980	
				81	2935	
				82	2685	3894
8523	60	4-11 1/4	4800	74	2150	
				74	2500	
				74	2320	2323
8621	63	10-2 5/8	4260	110	2685	
				110	2725	
				110	2985	2798
8622	64	10-0 3/8	3535	95	2975	
				95	2990	
				95	3118	3028
8623	63	10-1 1/8	4230		2145	
					2330	
					2422	2290
8721	63	14-11 1/2	2470	96	2770	
				96	2340	
				96	2365	2492
8722	64	14-11 5/8	2874	88	3230	
				88	3175	
				88	2900	3102
8723	65	14-11 1/2	3310	93	2630	
				93	2650	
				95	2770	2683
8821	64	19-7 1/2	2720	92	3590	
				92	3620	
				92	3860	3690
8822	66	19-6 1/2	1853	75	2560	
				75	2530	
				75	2905	2632
8823	63	19-6 1/2	2490	78	2915	
				78	2510	
				78	2820	2748

CONCLUSIONS.

The foregoing tests tend to show that :

1. Columns reinforced with longitudinal rods and spiral units fail at the middle, while plain columns and those reinforced with longitudinal rods only have no common method of failure.
2. Crooked joints, due to forms being out of line, are points of weakness.
3. The spherical bearing block causes the top of the columns to act as a hinged end in some cases, and the ultimate strength of the columns is decreased thereby; but to what extent cannot be determined by these tests.
4. No attempt has been made to account for variations in the strengths of similar columns, due to variations in mixing, in quantity or quality of cement, stone or sand.
5. The length has a decided effect upon the strength of columns reinforced with both longitudinal rods and spiral units.
6. The conditions of being out of plumb effects the strength of a column, but to what extent cannot be determined by these tests.
7. The effect of a reinforcement of 6-3/4-in. longitudinal rods is to increase the strength by about the same amount for all lenghts of columns between 5 and 20- ft.

8. The effect of a reinforcement of both 6-3/4 in. longitudinal rods and spiral units is to increase the strength of columns, and its efficiency increases with the decrease in the length of the column.
9. Reinforcement prevents a sudden failure; the reinforcement by both longitudinal rods and spirals being the most effective in this respect.